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TECHNICAL REPORT ECOM -5012-1

DEVELOPMENT OF CRITERIA AND MEASURES OF EFFECTIVENESS FOR U.S. ARMY TACTICAL COMMUNICATION SYSTEMS

FINAL REPORT

BY

G.D. WEINSTOCK -M. DOUGLAS -B. BLOM

MAY 1969

ECOM

DEVELOPMENT OF CRITERIA AND MEASURES OF

EFFECTIVENESS FOR U. S. ARMY TACTICAL

COMMUNICATION SYSTEMS

FINAL REPORT

CONTRACT NO. DAAB07-69-D-5012

Prepared By

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ABSTRACT

The purpose of this study is to develop a workable and valid method for measuring the effectiveness of the broad spectrum of U.S. Army tactical communication systems and equipments. To this end, an evaluation concept was formulated which provided an integrated system effectiveness model capable of providing a single explicit measure of system effectiveness for proposed tactical communication systems. The effort performed was divided into four parts: (1) the development of a comprehensive list of performance factors and effectiveness criteria which serve as input data to the model; (2) the development of matrices to relate military operations in the tactical environment and communication requirements; (3) to formulate analytic relationships between performance factors, criteria, and measures of effectiveness; and (4) to develop the system effectiveness model. The operation of the model is demonstrated by means of a sample problem.

FOREWORD

Within the framework of its Mission Area, the System/ Cost Analysis Office, USAECOM, is called upon to provide the Command and project managers with systems-analysis and cost-effectiveness studies necessary to support major program decisions. These analyses are often required on a quick reaction basis. USAECOM, therefore, contracted with Communications & Systems, Inc., to assist the Systems/Cost Analysis Office in performing Systems Analysis/Cost Effectiveness and special studies on a task assignment basis. This task, entitled:

"Task 3 -- Development of Communication Criteria and Measures of Effectiveness," has been prepared by Communications & Systems, Inc. in cooperation with the ECOM's Systems/Cost Analysis Office under contract number DAAB07-69-D-5012.

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INTRODUCTION AND SUMMARY

Paragraph 1.1 is a reproduction of the technical portion of the work assignment provided by the USAECOM Systems/ Cost Analysis office under contract No. DAAB07-69-D-5012.

1.1 WORK ASSIGNMENT

USAECOM
Systems/Cost Analysis Office
Work Statement - Task 3

DEVELOPMENT OF COMMUNICATION CRITERIA AND MEASURES OF EFFECTIVENESS

1. Objective of the Work Assignment

The objective of this task is threefold; development of criteria and performance factors to be considered when analyzing the effectiveness of competing communication equipment, nets, systems, or links; establishing formats for relating conflict intensity, mission assignment, tactical functions, and quantitative communication requirements of comm nets; and the development of relationships between communication performance criteria and factors and between criteria and measures of effectiveness.

2. Recommended Approach to be followed

This task is divided into four subtasks as follows:

a. Subtask 3A:

Develop a comprehensive listing of criteria and associated performance factors to be considered when evaluating the effectiveness of communication performance. (See incl 1 type format)

b. Subtask 3B:

Establish the format for each of three matrices. The first matrix will relate mission assignment to conflict intensity by frequency of occurence, and will relate allocation of resources to conflict intensity. (See incl 2.) The second matrix will identify the tactical functions in

each mission. (See incl 3.) The third matrix will provide
a format for relating quantitative communication require-
ments by comm nets to the individual tactical functions.
(See incl 4.)

    c. <u>Subtask 3C</u>:

        For the criteria and factors established under 3A,
develop quantitative relationships between the criteria and
factors, and between the criteria and measures of effective-
ness. If quantification cannot be accomplished, a quali-
tative relationship shall be provided.

    d. <u>Subtask 3D</u>:

        Using the items established in the three subtasks,
3A, 3B, 3C, show the procedure for measuring the effective-
ness of a proposed system.

<div align="center">

J. M. Slater
Task Leader

D. Salvano
A. Ruzgis
Contracting Officer's Representatives

</div>

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INCLOSURE 1: SUBTASK 3A: COMMUNICATION CRITERIA - PERFOR-
MANCE/EFFECTIVENESS FACTORS

CRITERIA	PERFORMANCE/EFFECTIVENESS FACTORS
RANGE	1. POWER OUTPUT 2. MODULATION 3. EMISSION 4. FREQUENCY 5. ANTENNAS 6. RECEIVER SENSITIVITY 7. TERRAIN 8. OTHER

MOBILITY	1. SIZE
	2. WEIGHT
	3. ROADABILITY
	   A. HIGHWAY
	   B. SECONDARY ROADS
	   C. UNIMPROVED ROADS
	   D CROSS COUNTRY
	   E. SLOPE
	4. AIR LIFT
	5. SLING LIFT
	6. NUMBER AND TYPE VEHICLES
	7. NUMBER AND TYPE POWER UNITS/TRAILERS
	8. PERSONNEL (TEAM SIZE)
	9. SET-UP TIME
	10. TEAR-DOWN TIME
	11. OTHER

NOTE:

1. The criteria developed for this subtask shall be
applicable to the total spectrum of communication
electronic equipments i.e., ground communication avionics,
surveillance, tactical satellite etc.

2. Performance/effectiveness factors shall include all
areas of consideration that may have an impact on the
established criteria.

INCLOSURE 2: RELATIVE RANKING OF MISSIONS/VARYING
LEVELS OF CONFLICT

MISSION ASSIGNMENT	CONFLICT INTENSITY		
	HIGH	MID	LOW
M_1			
M_2 REPRESENTATIVE ARMY TACTICAL MISSIONS	FREQUENCY OF OCCURRENCE		
M_3			
• • •			
M_x			
PERCENT OF RESOURCES			

NOTE·
1. HIGH INTENSITY CONFLICT = NUCLEAR ENVIRONMENT

2. MID INTENSITY CONFLICT = CONVENTIONAL ENVIRONMENT-POTENTIAL NUCLEAR THREAT.

3. LOW INTENSITY CONFLICT = STABILITY OPERATIONS.

4. A SURVEY WILL BE CONDUCTED OF SELECTED MILITARY PERSONNEL IN THE DA TO DETERMINE THE CONTENTS OF THIS MATRIX.

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TACTICAL FUNCTIONS.	F_1	F_2	F_3	•••			F_y	
MISSION ASSIGNMENTS								
M_1	1	1	0	1	0		1	
M_2	1	0	1	1	0		0	
M_3	1	0	1	1	1		1	
• • •.								
M_x	0	1	1	0	1		0	

REPRESENTATIVE ARMY TACTICAL MISSIONS

NOTE: 1. THE INSERTION OF "1" DENOTES THE TACTICAL FUNCTION IN THE MISSION ASSIGNMENT.

2. A SURVEY WILL BE CONDUCTED OF SELECTED MILITARY PERSONNEL IN THE DA TO DETERMINE THE CONTENTS OF THIS MATRIX.

INCLOSURE 4: QUANTITATIVE REQUIREMENTS OF COMMUNICATIONS
BY TACTICAL FUNCTIONS

TACTICAL FUNCTIONS	F_1	F_2	$\cdots$	F_y
COMM NETS				
1 VHF–FM LINE-OF-SIGHT TACTICAL NET				
2 HFSSB OVER-THE-HORIZON TACTICAL NET		QUANTITATIVE COMMUNICATION REQUIREMENTS		
3 VHF–UHF RADIO RELAY SWITCHED CIRCUIT COMMAND NET		THROUGHPUT ERROR RATE GRADE OF SERVICE ETC.		
ETC.				

NOTE:

1. FORMAT WILL PROVIDE FOR TABULATION OF QUANTITATIVE COMMUNICATION
REQUIREMENTS WHICH WILL BE DETERMINED AS APPROPRIATE FOR EACH
SYSTEMS ANALYSIS TASK.

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1.2 ORGANIZATION OF THE TASK EFFORT AND THE REPORT

In undertaking this task for the development of com-
munication criteria and measures of effectiveness, we rec-
ognize at the outset that the essential purpose is to
develop a workable and valid method for measuring the
effectiveness of Army tactical communication systems.
Everything which is done in this report is aimed toward
this single goal. To accomplish this we have developed
the evaluation concept shown in Figure 1-1. This diagram
in effect gives a birds-eye-view of the complete report.

To describe this concept, and also to show its com-
pliance with the contract work statement, let us first
summarize the four subtasks: (Table 1-1)

TABLE 1-1. SUBTASK SUMMARY

WORK STATEMENT SUBTASK	REPORT SECTION	DESCRIPTION
A	3	Develop comprehensive list of criteria and associated performance factors.
B	4	Establish formats for relating conflict intensity, mission assignment, tactical functions, and communication requirements
C	5	Develop quantitative relationships between criteria and performance factors and between criteria and measures of effectiveness
D	6	Show procedure for measuring effectiveness of proposed systems

The position of each of these subtasks in the evaluation
concept is shown in Figure 1-1 by the appropriate letter
and number designation. Section 2 of this report presents
the technical perspective upon which the complete concept
is based. The remaining sections, 3 through 6, correspond to
the subtasks A through D. Additional related information is
presented in the four appendices.

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The evaluation concept for a proposed communication system starts with the analysis of military operations such as force structure, mission assignments, and field activities. These are considered in the tactical environment of the battlefield and the conflict intensity of the engagements. From this we determine the quantitative communication requirements and the total military picture in which these requirements must be met. (Communication requirements may be specified by appropriate military authority. The model is not affected by this as long as all needed data is provided.) These requirements are expressed as the quantity of voice, data, and teletype between units; priority and routing information if known; and the perishability or required speed of delivery. This part of the concept fulfills the requirements of subtask B and is presented in Section 4. Illustrative tactical functions are presented in Appendices B and C.

The proposed communication system is considered in the tactical environment in which it is to function. We determine such descriptive data as equipment compliment, network configuration, operating procedures and military personnel assigned to all phases of the operation related to communications. This in turn gives rise to a detailed list of performance elements or factors such as capacity, range, reliability, hardness, size, weight, tear-down time, and set-up time. All of these performance factors serve as input data to the system effectiveness model. They are first grouped together under appropriate functional headings termed effectiveness criteria such as mobility, transportability, survivability, dependability etc. This portion of the work is reported in Section 3 and complies with Subtask A.

The performance factors and effectiveness criteria must now be converted to a suitable input format for the integrated system effectiveness model. This is accomplished by a series of analytic or quantitative relationships between performance factors, criteria, and the measures of effectiveness. These can be described in effect as submodels or effectiveness criteria models. Section 5 of the report discusses this effort which also complies with Subtask C of the work statement.

The integrated system effectiveness model combines all of the input data into a single explicit value of system effectiveness. This takes into consideration the intrinsic benefit that can be obtained from the performance capability,

Figure 1-1. Evaluation Concept for Army Tactical Communications
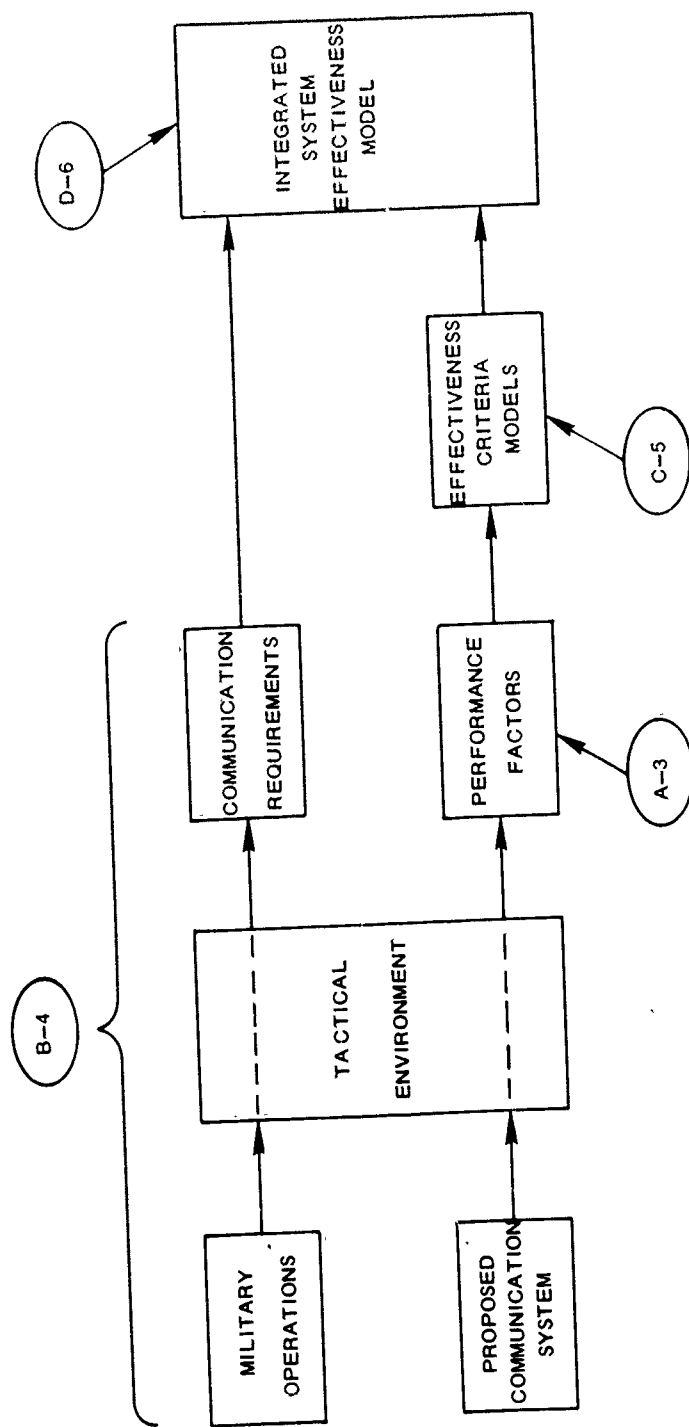
LEGEND:

LETTERS DESIGNATE WORK STATEMENT SUBTASKS

NUMBERS DESIGNATE SECTIONS IN THIS REPORT

the operational readiness of the system, the continuity of
performance, and finally the risk factor if any parts of
the system are proposed future developments. The technical
basis for this model is established in Section 2 and a step
by step explanation of the model together with a sample
problem is presented in Section 6. This part of the con-
cept fulfills the requirements of Subtask D. Appendix A
contains the derivation of the probability equation used
in the model and Appendix D contains the calculations for
the sample problem.

1.3 CONCLUSIONS AND RECOMMENDATIONS

This report presents an integrated system effective-
ness model which is capable of providing a single explicit
measure of system effectiveness when evaluating competing
communication equipments, networks and systems which con-
stitute the scope of U.S. Army tactical communications. In
the areas of listing the performance factors, criteria, and
measures of effectiveness; and the formulation of analytic
and quantitative relationships the work was carried to
sufficient depth to complete the formulation of the system
effectiveness model. We can anticipate that further work
will be desirable in these areas at such time as subsequent
phases of this model development are undertaken, such as
computerizing the model.

Since this model is based on statistical analysis and
the probability of successful communications derived from
queuing relationships, it will not suffer from the high cost
and complexity of the more sophisticated event-by-event
model. This has proved to be a significant advantage in
the application of this technique in that it improves the
efficiency of the simulation process.

It appears desirable at this time to test the model and
evaluation concept by means of a test problem. This should
be a non-trivial case, but preferably not too complex to
permit the computation by essentially manual means. Some
simple computer assistance can be provided in the solution
of the probability equations, while the remainder of the
model is exercised manually. If possible the test problem
should also be run on other modeling facilities to obtain a
check of the answers computed. The completion of a test
problem will not only establish confidence in this model,
but also provide valuable insight into the models operation.

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This will prove fruitful in the later phase of computerizing the model. This last step of computerizing the model is essential if any extensive use of the model is to be achieved.

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SECTION 2

TECHNICAL PERSPECTIVE

While this task is specifically concerned with the development of communication criteria and measures of effectiveness, to provide generally valid results we are obliged to first view the problem in the larger perspective of systems analysis and cost-effectiveness studies.

At the outset we deem it appropriate to formulate the frame of reference encompassing the technical work to be performed. By so doing we establish the technical perspective upon which the entire structure rests. It is our intention to show that a priori assumptions are kept to a minimum and that each stratum of the method is evolved by reasoned and logical development.

2.1 REASONS FOR A COMPREHENSIVE STUDY

The type of comprehensive study known as systems analysis and cost-effectiveness has come into prominence in the past decade as a result of increasing complexity and cost in military systems, which place an increasing demand on our national resources. Specialists in military science are familiar with the importance of resources to national defense. It is generally recognized that in the event of war the winning side is likely to be the one having the greatest resources, provided those resources are used efficiently.

The purpose of the comprehensive study (system analysis and cost-effectiveness) is to ensure the efficient use of resources through the marriage of engineering and economic analysis. Hitch and McKean[1] have shown that this objective is achieved under either of the following conditions:

a. The least cost system to meet the required performance capability has been selected.

b. The maximum performance capability that can be obtained for a specified cost has been selected.

At every level of government concerned with the use of resources, the decision maker is invariably faced with the dilemma of many alternatives and limited budgets. These

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alternatives are the means at his disposal to achieve the
desired objective and they are also the contenders for the
limited budget. Hence, the end product of a comprehensive
study must be to place before the decision maker a true rep-
resentation of cost versus benefit for all reasonable and
appropriate alternatives.

2.2 MEANING OF TERMS USED HEREIN

In this discussion we will frequently use the following
key words: requirement, performance, capability, effective-
ness, and benefit. Perhaps it will be of value to devote
some space to the meaning of these words and the way they
are used in this report. From the dictionary we have se-
lected the following meanings as the ones that come closest
to their usage in this report.

>   requirement: something wanted or needed
>
>   performance: the manner of carrying out prescribed
>   functions
>
>   capability: the capacity for an indicated use
>
>   effectiveness: the production of a desired result
>
>   benefit: something that provides a useful advan-
>   tage

It is interesting to note that each of these five words
can be used to describe the same quantity in a system, but
from a slightly different point of view. The requirement
is the system quantity that is wanted or needed without re-
gard to how it will be fulfilled. Performance, on the
other hand, describes how the requirement will be fulfilled.
While a numerical value is usually associated with a re-
quirement, such is not the case for performance until we
add the additional ingredient, capability. Thus, perform-
ance capability is the capacity (numerical value) for an
indicated use, namely the carrying out of prescribed. func-
tions.

This term (performance capability) is still not ade-
quate for our purposes because it implies that more of a
good thing is even better. We know that this is not nec-
essarily true. Performance capability that far exceeds the
requirement may not be desirable. Thus we introduce

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effectiveness, which is the production of a desired result. The assumption here is that the requirement is the desired result. As usually expressed, effectiveness is the probability of meeting the requirement. This is to say the probability that performance capability will equal the requirement. Since this is an expression of probability, its maximum value is 1 or 100%.

Unfortunately, the requirement is not always known or perhaps it is expressed as a range from minimum need to a desirable value. Furthermore, performance capability that exceeds the requirement may still be useful. We therefore resort to the additional word "benefit," which is something that provides a useful advantage. Hence, benefit can be measured as the performance capability derived from the system so long as it provides a useful advantage. The measure of benefit is a more general tool than effectiveness because it is not limited by the specified requirement, and also, it can be expressed in units and dimensions of performance capability that are intimate to the system.

To illustrate the relationships between these terms, we construct the scales shown in Figure 2-1. Scale A is in units of performance capability, and its maximum value is limited only by technology and resources. For example, if the performance capability is determined by the number of channels, we could conceivably go on adding channels forever. If a requirement has been specified B we can construct the effectiveness scale C. Here the maximum value is 1 or 100% because it is the probability of fulfilling the requirement. The benefit scale D is in the same units as performance capability, but its maximum value is limited to that level of performance capability that provides a useful advantage.

We can, if we wish, construct a normalized benefit scale by dividing the benefit scale by the requirement. This would be essentially the same as the effectiveness scale, differing in only one respect. While the effectiveness scale stops at 1, the normalized benefit scale may be greater than 1.

2.3 THE BENEFIT OF TACTICAL COMMUNICATION

The determination of benefit is frequently a source of some controversy because proponents of a system naturally tend to desire or claim far-reaching benefits. This difficulty can be minimized by recognizing the proper
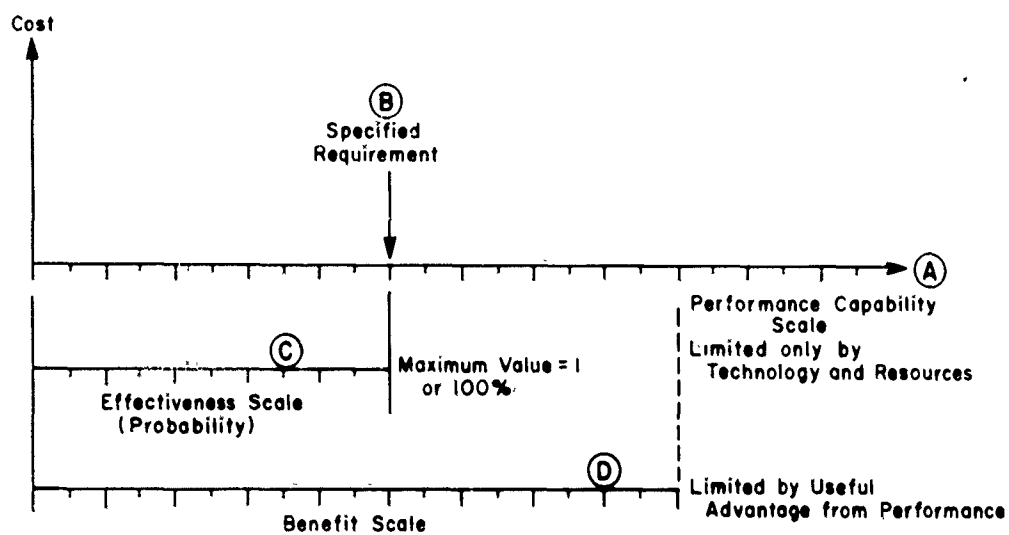
Figure 2-1. Comparison of Measuring Scales for Performance Capability, Effectiveness and Benefit

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jurisdiction of the decision maker and the essential nature of the alternatives he must evaluate. The valid formulation of benefit describes the essence of the advantage to be gained, which is intrinsic to the system being considered. In other words, benefit is the sum of the useful quantity obtained directly and entirely from within the proposed system.

The essential nature of a communication system is that it transfer information. This means the exchange of voice, teletype, or data between two or more geographic locations and within a finite time delay. In the tactical environment, the communication network provides a support function to the field commander and the military force structure at all levels from the foot soldier to the field army. In so doing, the information transferred is a useful quantity if the following three conditions have been met:

a. A military need existed to transfer the information between separated locations.

b. The information transfer has been successful, that is, received and understood, within acceptable bounds of quality or error rate.

c. The information arrived at the destination in a timely fashion, appropriate for the intelligence which it contains.

Based on this analysis, we can formulate the following definition: The benefit to be obtained from a tactical communication system is the timely transfer of information needed in the tactical environment.

An example of the controversy that enters the picture at this point is found in the suggestion sometimes proposed that we measure communication benefit in terms of combat capability. While it is certainly true that communication benefit will contribute to combat capability, all of the other elements of the force structure also contribute. Combat capability is too far-reaching because it is clearly more than an advantage gained directly and entirely from the communication network. Perhaps combat capability is the measure of benefit to be derived from the military force structure, but this is beyond the subject of the present task.

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2.4 QUANTIFICATION OF BENEFIT

Based on the definition of communication benefit, we now proceed to quantify it. First we establish the dimensions of the measure. Essentially there are only two, information and time. There will, of course, be a natural tendency to introduce importance as another dimension but, while importance determines the priority of the traffic, it is not a quantity generated by the facility and hence is not a measure of benefit obtained from the facility. The communication system delivers only two useful quantities: needed information and required speed. We therefore establish the dimensions of benefit as follows:

$$\text{Benefit} \quad = \quad \begin{bmatrix} \text{Needed} \\ \text{Information} \\ \text{Transfer} \end{bmatrix} \quad x \quad \begin{bmatrix} \text{Required} \\ \text{Speed} \end{bmatrix} \qquad (2-1)$$

We do not mean to say that importance is ignored, far from it. The importance of the traffic will show up in the measure of benefit in two ways. First, important traffic will have higher priorities and will therefore be the first benefit quantity accruing to the credit of the system. Secondly, there is usually a direct correlation between importance and required speed of delivery, hence the value of the traffic being proportional to required speed is also proportional to its importance.

To establish the approriate units for benefit, we recognize that communication benefit is a quantitative measure whereby the capacities of different systems to transmit information may be compared. There is a long history of investigation in the field of information theory that, according to Woodward[2], was started by Hartley[3] in 1927 and followed by others, notably Shannon and Weaver[4]. The concepts can be considered for communication systems in which information flows continuously or for information storage. The key point is that the information content of a message may be defined as the minimum capacity required for storage. The information capacity of a system is given by the expression

$$C = \log n \qquad (2-2)$$

where n is the number of states. For example, a 5 bit register in a binary system may hold up to 32 states, hence

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$$C = \log_2 32 = 5$$

or the information contained in the register is 5 bits provided there is no redundancy.

If we can predict that certain states will occur with a certain probability P, the information in that state is

$$H_p = - \log P \qquad (2-3)$$

expressed in the exponential form for base b

$$(b)^{H_p} = \frac{1}{P} \qquad (2-4)$$

from which we see that as the probability approaches 1 the information approaches 0.

To illustrate this, suppose a communication channel were being used to transmit the time of day every minute where the receiving station has a clock in good working order. Since every message beyond the first can be predicted with a probability close to 1 the information content is nil.

Thus the average information per message is given by Shannon as

$$H = - \sum_i P_i \log P_i \qquad (2-5)$$

which is to say for each possible state we have the probability of occurrence times the information it contains summed for all states.

If there is no redundancy and no advance information, all states are equally probable and the message contains the maximum information as in equation 1.

$$H_{max} = C = \log n \qquad (2-6)$$

Hence, as Woodward[2] points out, binary messages whose states are equally probable cannot be condensed, and there is no more economical way to store them than to put each message separately into a binary storage unit.

Highly formatted data transmission may have transmission rates of 600, 1200, or 2400 b/s. For this we can estimate a control redundancy of one parity for each eight bits plus six control characters for each 86 groups. Thus, the control redundancy is

$$\frac{128}{688} = 18.6\%$$

and the overall redundancy may be estimated as 20%.

In voice communication, a reasonable assumption for speaking rate is 180 words per minute or 3 words per second. Considering an average of 5 characters per word and 7 bits per character, we have a theoretical bit rate of 105 b/s. Actually, it has been demonstrated that the spoken word contains a redundancy factor of approximately 7:1, which would suggest that the effective information transfer rate of voice was 105 divided by 7, or 15 b/s. We believe this figure is somewhat low because it does not include such information as voice recognition, emotional content, sense of urgency, emphasis, and the ability to obtain prompt feedback for acknowledgment and error correction. Recent experiments with voice communication through narrow bandpass filters have shown that the basic intelligence without quality can be transmitted within a bandwidth of 25 Hz. This suggests that a suitable estimate for voice communication is an information transfer rate of 25 b/s.

For a teletype communication of 60 words per minute or 1 word per second, we have a theoretical bit rate of 35 b/s. If the messages are in ordinary language with a redundancy factor of 7:1, the effective information transfer rate is only 5 b/s. On the other hand, highly formatted messages may contain a transfer rate as high as 25 b/s.

One additional factor that needs to be considered in the transfer of information is preparation time. Since teletype and data circuits require special terminal equipment and operator skills, they are not normally connected user-to-user as is the case for the telephone. For this reason, the total time to deliver a message from source to destination must consider not only the network delay and transmission time, but also the message preparation time for teletype and data. An average value for preparation time is estimated to be 30 minutes for important traffic and 120 minutes for routine traffic.

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Table 2-1 presents a summary of the information transfer rates and related data for voice, teletype, and data communication.

We are now prepared to define the unit of communication benefit and to illustrate the computation for typical messages. In equation 1

$$\text{Benefit} = \text{Information} \times \text{Speed}$$

wherein the unit of information is the bit and the unit of speed is the reciprocal of the allowable delay in seconds. Hence:

$$1 \text{ Benefit Unit} = \frac{1 \text{ info bit}}{1 \text{ delay second}} \qquad (2\text{-}7)$$

or, expressed in words, the unit of communication benefit is one information bit per delay second. To illustrate, consider the following messages:

a. 2 call-minutes of voice, allowable delay 4 minutes

$$B = \underset{\text{bits}}{(2 \times 60 \times 25)} \ \underset{\text{delay sec.}}{(\frac{1}{240})} = 12.5 \text{ bits/delay sec}$$

b. 2 channel-minutes of 600 b/s data, allowable delay 6 hours

$$B = \underset{\text{bits}}{(2 \times 60 \times 480)} \ \underset{\text{delay sec.}}{(\frac{1}{6.60.60})} = 2.67 \text{ bits/delay sec}$$

Thus we have a means of combining the benefit of voice, teletype, and data traffic of different precedences into a single explicit measure of benefit that is needed in the overall study procedure. We believe this technique has reasonable validity and we recognize that it contains parameters that are hard to measure accurately, such as preparation time. Other methods of combination may be developed, but we have not encountered any to date. This one, by C&S, appears to be the best available.

TABLE 2-1. SUMMARY OF INFORMATION RATES FOR VOICE, TELETYPE AND DATA

Mode	Traffic Load	Transmission Rate	Information Transfer (b/s) Rate	Preparation Time
Voice	Call-minutes holding time	4 kHz channel	25	Nil
Teletype	Message length in words or groups	60 wpm	5 (ordinary language) 25 (formatted)	30 minutes for priority traffic
		100 wpm	8 (ordinary language) 40 (formatted)	To
Data	Message length in bits or kilobits	600 b/s	480	
		1200 b/s	960	120 minutes for routine traffic
		2400 b/s	1920	

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2.5 THE STUDY PROCEDURE

It is customary to start a comprehensive study with analysis of the operational missions to determine a feasible and useful range of system requirements. This usually involves the use of war games between the classic blue and red forces or, at the very least, detailed mission scenarios representative of the actual situations. The results of this part of the analysis will be most beneficial to the study if the following guidelines are observed:

a. Requirements should be expressed in terms commensurate with the performance benefit desired. For example, a communication requirement should be expressed as information transfer and speed rather than channels.

b. The range of requirements should be established with the boundaries as wide as possible to provide the decision maker with the greatest degree of choice.

c. The war games, mission scenarios, and the data derived from the operations analysis should be in a form suitable for the later step of modeling and evaluating alternative systems.

This is followed by a review and assessment of the technology to determine feasible techniques, concepts, and systems that may be employed to provide the desired performance benefit. These in turn form the basis for developing alternative systems through tradeoffs within the technology and feasible combinations of major components. By this process, we have presumably established all reasonable alternatives for meeting the objectives of the study. There remains only the crucial step of evaluating these alternatives by determining the amount of performance benefit that can be predicted for each one.

So far, little has been said on the subject of costs. This is not to minimize the importance of cost in the evaluation process. Actually the techniques for compiling life-cycle costs are relatively straightforward, and, furthermore, according to the work assignment the part of costing in the comprehensive study was intentionally excluded from the scope of this task.

2.6 MODELING TECHNIQUES

The evaluation procedure starts with the modeling of each proposed system. There are, generally speaking, three broad methods of modeling that are reasonably applicable to this comprehensive study. The first method is stochastic simulation, which represents the war games or mission scenarios event by event as a function of time. While this first method is the most believable model because of its verisimilitude, it is also the most expensive to develop and the most expensive to use after it is developed.

The second method is a probability model based upon steady-state conditions during a period of heavy load. This type of statistical model, sometimes known as a busy-hour model, estimates the probability of success for the performance benefit desired. It is based upon a number of assumptions, some of the more important ones being the following:

    a. The steady-state traffic load during the busy hour represents the major demand on the system.

    b. Changes in the system flow consisting of traffic events, system down time, quality deterioration, et cetera are random variables with the probability of occurrence in any one instant being the same as in any other instant of time.

    c. The status of the system may be characterized as a series of possible states, some of which represent satisfactory or successful performance and the remainder represent a condition of failure. Then, based on probability theory:

$$\frac{\text{Probability}}{\text{of Success}} = \frac{\text{Sum of Successful States}}{\text{Sum of All States}}$$

The probability model is much less costly to develop and also less costly to use after it is developed. It has the disadvantage of being less believable because of the lower degree of verisimilitude. The validity of the model, however, is probably comparable to the stochastic simulation.

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Finally, there is the third method based upon weighted scores determined by engineering judgment. This method is certainly least costly of all, but also probably has the least validity. It assumes that a series of intuitive judgments, which are then summed for the total score, has greater validity than one overall intuitive judgment. Although it is still sometimes used, it is not recommended.

To illustrate these three methods, consider the problem of the probability of throwing the number seven with a pair of dice. This can be solved by the three models just described as follows:

1. Program a computer to select and add two numbers chosen at random from one to six with equal weight to any number. Perform ten thousand trials and record the number of times the sum equals seven. The ratio of success over total trials is the probability desired. (Admittedly, in this example the events are not really changing with time.)

2. Construct the matrix of possible states as follows:

Dice A/B	1	2	3	4	5	6
1	2	3	4	5	6	7
2	3	4	5	6	7	8
3	4	5	6	7	8	9
4	5	6	7	8	9	10
5	6	7	8	9	10	11
6	7	8	9	10	11	12

We observe a total of 36 states of which 6 give the desired value, hence:

$$P(7) = \frac{6}{36}$$

3. Go to Las Vegas and take a poll of the people at the dice tables, asking each person what he believes is the probability of throwing a seven with the dice. Average the answers using a heavier weighting for those who appear to be more seasoned gamblers.

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2.7 CHOOSING THE APPROPRIATE MODELING TECHNIQUE

In the choice of modeling technique for tactical com-
munication networks, we are inclined to rule out the
weighted scoring technique because the results are strongly
subjective. This means the answers are likely to be dif-
ferent for different groups assigning weighting values
and the results can be easily biased if there is an inclina-
tion to do so. Of the three methods available, this one is
the least defensible and the one most easily shot down by
the losing contenders in the decision process. They will
probably argue for a set of weighted values that completely
reverses the decision or at least shifts it in their favor.

Event-by-event simulation and its many variations can
be considered to be ideal simulation except that the use of
this technique for large and complex systems has proven to
be almost prohibitively expensive. Even the invention of
higher-order simulation languages has not reduced the costs
significantly. Also, due to inefficiencies in the simula-
tion languages, running time may be slower than real time
if there is considerable detail in the simulation. In
other words, to simulate two hours of network operation
might take four hours on the computer.

For the purpose of this task, we believe the second
method employing probability techniques is the best choice.
Even though careful study is required to demonstrate its
validity, it is by far the fastest and least costly method
of modeling the tactical communication networks.

The basic principle employed in the development of a
probability model is to identify all possible states in
which the system can exist and determine the probability
of each state. This principle is employed over and over
again on many levels and on a variety of applications, but
the basic idea is always the same.

2.8 CRITERIA IN THE BENEFIT MEASURE

Consider first that we have a proposed network and wish
to write a general expression for the benefit that can be
expected. Let us also assume that, under ideal conditions,
the maximum performance capability has a useful advantage
and hence is the quantity of intrinsic benefit (B_i) that

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can be produced. If there were no factors to detract from this ideal condition, we could say that the measure of benefit (B) is the same value

$$B = B_i \qquad\qquad (2\text{-}8)$$

Ideal conditions, however, only exist in theoretical analysis. In the real world we are dealing with tactical equipment that must be moved from place to place. During these periods of transport, which involve tear-down, travel, and setup times, part or all of the system will be inoperative. We must therefore account for all' possible states of operational readiness (O) and the probability of each state. This introduces the first modification to equation 8:

$$B = f(B_i, \ o) \qquad\qquad (2\text{-}9)$$

Similarly, in the real world we are dealing with equipment that has finite reliability and is subject to enemy destruction or jamming. These factors involve mean time before failure (MTBF), mean time to repair (MTTR), hardness to enemy action, and resistance to enemy countermeasures. Since part or all of the system may become inoperative, we must account for all possible states of the continuity of performance (C) and the probability of each state. This introduces another modification, and equation (9) becomes:

$$B = f(B_i, \ O, \ C) \qquad\qquad (2\text{-}10)$$

Finally, since we are usually evaluating a proposed system for a future time frame, there is a risk factor (R) that part or all of the system to be developed will not exist at all. As before, we account for all possible states of risk and the probability of each. This gives us the final form of the general expression:

$$B = f(B_i, \ O, \ C, \ R) \qquad\qquad (2\text{-}11)$$

The measure of benefit is a function of all of the possible system states which determine the intrinsic benefit (B_i) and all of the possible states of operational readiness (O), continuity of performance (C), and risk factor (R).

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2.9 BASIC MODEL ASSUMPTIONS

In modeling the communication system in the tactical
environment, we need to consider network configurations,
traffic load (user distribution and time urgency), and
routing. The evaluation of the proposed system is based
upon the measure of benefit, that is, the useful performance
capability during the period of heaviest demand. Thus, we
examine the war game scenarios and determine a composite
traffic distribution, which may be described as the need
lines as a function of time. The battle may last a few
hours or many days, but the period of heavy demand may
still be only one hour to possibly half a day.

During the busy period, we assume a steady-state
condition with respect to the traffic. While the number
of messages will be fluctuating at any instant, the average
over a significant interval is assumed to be the same as
the average over the full busy period. This assumption is
a condition of statistical equilibrium, which is to say
that the probability of traffic entering the system is the
same as the probability of traffic leaving the system during
this busy period. Expressed in different words, the average
arrival rate for new messages is equal to the average ter-
mination rate for messages being completed or leaving the
system for other reasons.

The components of a communication system consist of
a variety of devices and facilities including handsets,
radios, teletype machines, card and paper devices, channels
and trunks, technical control facilities, circuit switches,
and store and forward switches. As complex and varied as
these devices are, they all do one of four things to infor-
mation: transform, store, process, and transmit.

Terminal devices, for example, transform information
from voice, hard copy, or visual data to electrical signals
and back. Storage may take place in computer core memory,
magnetic or paper tape, punched cards, drums, discs, and
even in the memory of the telephone user. Processing
concerns signaling to establish circuits or the handling
of store and forward messages, the setup of radio links,
and the assembly and disassembly of messages. Finally,
transmission involves circuit holding time, data rates,
HF radio, satellite, tropo links, et cetera.

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All of these functions can be represented as sets of
series or parallel facilities, each of which can perform
a service function. This is to say that every separately
identifiable component of a communication system can be
represented as a device that performs a service in the
transfer of information. This service may be to transform,
store, process, or transmit. We therefore consider the
structure of the basic component of the system to be a set
of facilities as depicted in Figure 2-2.

A.
FACILITIES TO TRANSFORM
PROCESS TRANSMIT

B.
FACILITIES TO STORE
THE QUEUE WAITING FOR A.
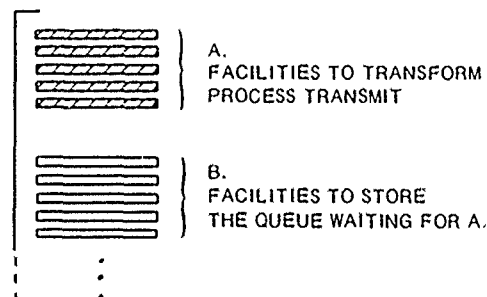
Figure 2-2.   Representation of Parallel Facilities

Given that we are representing one set of facilities
for a particular function, Figure 2-2 shows a set of five
shaded facilities (group A) which might be channels in a
trunk, stages in a register, or paths through a switch.
The five or more unshaded facilities (group B) represent
storage for traffic waiting in queue for group A. These
storage facilities may be physically real, or mental as in
the case of a caller waiting for a telephone connection.

We are concerned with three variables in the traffic
parameters, the time between messages, the duration of the
message, and the delay in queue.

Associated with each of these three variables is a
critical event that coincides with the expiration of a
time interval. When the time between messages expires,
we have the event of a new message; when the time of dura-
tion expires, we have the termination of a message; and
when the delay in queue exceeds the perishability, we have
a worthless or expired message.

The further development of this modeling technique
employs information from probability theory and queuing
for which many references can be found. We are not pre-
pared to cite a particular reference because, even though
the theories are generally known, no one text treats the

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subject exactly in the manner we have here. It is customary to credit Poisson, Erlang and others with being the original researchers in the field, and the New York Telephone Company and Bell Laboratories of AT&T have prepared extensive technical notes and textbooks on the subject. Conceivably, a literature search would identify several appropriate references including such authors as Feller,[5] Syski,[6] Reuter and Lederman,[7] and Morse[8].

We assume that the events determined by the traffic parameters are random variables and that their probability of occurrence in any one instant is the same as in any other instant. The significance of this assumption is two-fold, for it allows us the convenient form of the exponential distribution that lends itself to ease of mathematical solution and it says that the probability of the event taking place in any one instant is not influenced by what has just gone before. For example, given an average message arrival rate, the probability of a new message arriving is the same regardless of whether or not another message has just recently arrived. This assumption is not entirely rigorous; and in one case, holding time is too severe. The same model can be developed for arbitrary holding-time distributions, but the mathematics becomes more complex. See Appendix A for the derivation of the probability equation used in the model and the method of solution employing two algorithm tables. In the application of these queuing relationships, certain approximations are made with respect to priority categories. It may be that some further rigorous treatment can be considered when this model is computerized.

SECTION 3

CRITERIA AND PERFORMANCE FACTORS

As stated in Section 1, the proposed communication
system is considered in the tactical environment in which it
is to function. We determine such descriptive data as equip-
ment complement, network configuration, operating procedures
and military personnel assigned to all phases of the opera-
tion related to communications. This in turn gives rise to
a detailed list of performance elements or factors such as
capacity, range, reliability, hardness, size, weight, tear-
down time, and set-up time. All of these performance factors
serve as input data to the system effectiveness model. The
purpose of this section is to develop this comprehensive
list of performance factors and effectiveness criteria.

The criteria postulated to cover the scope of U.S. Army
tactical communication systems are listed in Table 3-1. Each
of the criteria has associated with it a group of directly
relatable performance factors. In addition to the table, a
description is provided for each of the criteria to amplify
its impact on successful system operation.

The first criterion on the table is transportability.
The majority of tactical communication systems will require
transportation from one location to another in fulfilling
their tactical functions. Depending on the size and weight
of the system the time and resources to transport it from
one place to another vary considerably. The general set of
performance factors that are associated with transportability
are size, weight, number of vehicles employed, and roadabil-
ity, that is, the type of terrain over which the system must
be moved.

Where transportability is concerned with transient time,
mobility is involved with the speed of packaging the system
for transit after stopping operation and reconstructing it
after arrival at the new location. Mobility also depends on
the system performance elements of size, weight, number of
personnel, and the speed in which the system can be torn
down and set up.

In order that a system be able to satisfy the traffic
density imposed upon it, it must have sufficient communica-
tions capacity. If the traffic is analog (voice) then the

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TABLE 3-1. EFFECTIVENESS PERFORMANCE PARAMETERS

CRITERIA	PERFORMANCE FACTORS (ELEMENTS)	CRITERIA	PERFORMANCE FACTORS (ELEMENTS)
Transportability	Size Weight Number of Vehicles Roadability	Reliability and Availability	Mean Time to Repair Mean Time Between Failures Mission Time Network Configuration Number of Repairmen Number of Spares
Mobility	Set-up Time Tear-down Time Crew Size	Maintainability	Mean Time to Detect, Isolate Isolate and Repair Fault Number of Spares Number ... Scheduled ...nance Intervals
Capacity a. Analog (Voice)	Link Capacities (Channels) Network Configuration Traffic Flow (Routing)	Operability	Number of Personnel Skill Level Training Time Personnel Facilities
b. Digital (Data)	Link Bit Rates Link Capacities (Channels) Network Configuration Traffic Flow (Routing)	Security	Message Encryption Traffic Encryption Physical Plant Security
Quality of Service a. Analog (Intelligibility)	Signal-to-Noise Ratio Noise Distribution Modulation	Realizability	Time Frame Resource Availability
b. Digital (Error Rate)	Modulation	Range	Power Output Modulation Scheme Frequency Antenna Medium Receiver Sensitivity
Survivability	Static & Dynamic PSI Hardness Distance of Target Weapon Yield Time Period Weapon Accuracy Radiation Level		
Vulnerability	Signal-to-Jammer Ratio Modulation Type Medium Receiver Susceptibility		

network configuration and the individual link capacities
determine capacity. If the traffic is in digital form then
in addition to the above factors the link data rates estab-
lish overall capacity. In general, the traffic is of a mixed
mode; voice, teletype and data.

Quality of service determines if the information is
received. If the information is analog (voice) then intelli-
gibility is the measure of service quality. Intelligibility
is dependent on the signal-to-noise ratio, the noise distri-
bution and the modulation scheme. If the information is
digital, then error rate is the measure of quality.
The error rate is dependent on the medium, error distribu-
tion, error code employed, and the modulation scheme. In
either case, if the quality of service is below the accepta-
ble level the information will have to be repeated and the
result is a lower information transfer rate.

Any system which operates in a military environment is
subject to overt attack. In order to protect against this
possibility, the system must be physically protected. The
survivability, therefore, of the system is dependent on such
factors as pressure hardness, weapon yield, radiation level,
time period, weapon accuracy and target distance.

In addition to overt attack, a military system is also
subject to covert attack which primarily is of electronic
means. The measure which denotes this type of system sensi-
tivity is referred to as vulnerability. Vulnerability is
dependent on signal-to-jammer ratio, modulation type, medium,
and receiver susceptibility. There are two basic means by
which a system can be interfered with electronically. They
are jamming (which involves overpowering the communication
system), and deception (which employs sophisticated tech-
niques for causing system interference and hence introducing
errors without this fact becoming known to users of the com-
munication system). In either case the result is a loss of
information, which lowers the systems information transfer
rate.

Availability is indicative of the state of the system
at any arbitrary time of access. Reliability specifies the
state of the system during a predetermined mission time and
is directly dependent on the duration of the mission period.
The performance elements are mean time between failures,
mean time to repair, number of repairmen, number of spares,
and network configuration. Mission time is a factor in
reliability, but not in availability.

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Two aspects of maintainability have to be considered, scheduled repairs at predetermined intervals and unscheduled repairs due to catastrophic failures. The elements which constitute a determination of the mean repair time are mean time to detect, locate, and isolate a fault, the number of spares, and the number of repairmen. The latter two elements are also included in the determination of the appropriate interval for scheduled maintenance.

Operability relates to the personnel requirements for the actual system. It includes the number of personnel, the skill levels, the training time, and the facilities required to house the personnel. This criterion will also affect mobility, transportability, and system cost.

A communication system operating in a tactical environment must be provided security in order that the information transferred and processed does not fall into enemy hands. There are two kinds of security to be considered. The first type involves the physical protection of the communication facilities by use of troops. The second and more sophisticated type involves the use of cryptographic equipment coupled with Time Division Multiplex and Electronic Switching. This latter mode permits two forms of security: message security by direct encryption techniques and network or traffic flow security between users by means of bulk encryption at each mode. This latter technique provides for the trunks between all modes to be fully occupied whether or not real messages are being transmitted. The generation of dummy messages combined with real messages protects the direction of flow of the actual messages.

Realizability refers to the time frame in which the system is expected to function. The question asked is whether the candidate under evaluation is realizable in that time frame. If the candidate system is composed primarily of state of the art equipment, there is no difficulty in determining its realizability. If the candidate, however, involves techniques and materials which are presently beyond the state of the art, then the probability of achieving the design within the time frame and available resources must be determined.

The range of a system depends on a number of performance factors. The most significant of these factors are power output (i.e., effective radiated power), the modulation scheme employed, the frequency of transmission, the antenna characteristics, the medium, and the receiver sensitivity.

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These performance factors and criteria will be used in the criteria models of Section 5 and in the integrated system effectiveness model in Section 6.

SECTION 4

TACTICAL OPERATIONS AND REQUIREMENTS MATRICES

In the evaluation of competing communication systems
we start with the analysis of military operations such as
force structure, mission assignments, and field activities.
These are considered in the tactical environment of the
battlefield and the conflict intensity of the engagements.
From this we determine the quantitative communication
requirements and the total military picture in which these
requirements must be met. (Communication requirements may
be specified by appropriate military authority. The model
is not affected by this as long as all needed data is pro-
vided.) These requirements are expressed as the quantity
of voice, data, and teletype between units; priority and
routing information if known; and the perishability or re-
quired speed of delivery. The purpose of this section is
to develop the formats for accomplishing this.

4.1 TRAFFIC CATEGORIES

Tactical military traffic can be divided into two broad
categories. Some traffic is predictably repetitive in
nature. This traffic is generally concerned with personnel
matters or is administrative or logistical in nature and
normally carries a routine precedence. Examples of this
type of traffic are situation reports, personnel daily sum-
maries, requisitions, personnel actions, American Red Cross
traffic, et cetera.

These reports are made daily and are almost independent
of the situation. Repetitive traffic therefore represents
a sort of minimum level or bias on the system upon which
other traffic is superimposed. This bias, however, is not
a constant value over the day. This traffic will tend to
peak during the daylight hours, possibly around mid-morning
and late afternoon. If a busy-hour-to-average daily ratio
has not been established for this type of traffic, it will
have to be developed through a time analysis.

Some of these reports are spelled out in Army manuals
while others are imposed by higher command. The development
of traffic statistics on this repetitive traffic can there-
fore be accomplished through the perusal of appropriate
Army manuals and consultation with experienced field officers.
The appropriate service schools, particularly the Adjutant

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General's School, should be a major source for information on this repetitive traffic.

In addition to repetitive traffic, there are other demands on the communication system that are a definite function of the situation. This second type of traffic, since it is irregular in occurrence, will be called the irregular traffic to differentiate it from the repetitive traffic. This type of traffic is usually characterized, in comparison with the repetitive traffic, by shorter holding times, shorter perishability, a higher percentage of voice traffic, and a higher busy-period-to-average daily traffic ratio. It is the handling of this traffic that will stress the communication system the most.

Since this irregular traffic is a function of the situation and since no two situations are exactly alike, requirement determination for this type of traffic is a difficult problem. Since it is this irregular traffic that stresses the communication system, the problem must be resolved if a realistic method of evaluating system performance is to be developed. Emphasis is therefore given to the development of a technique for the determination of these irregular requirements. It must be kept in mind that this irregular traffic is superimposed on the repetitive traffic.

This division of tactical military traffic is simply a convenience in analyzing the problem. It does not imply that the two types will be treated differently in the model. Even though different techniques are used to derive them, they must be expressed in an identical manner to permit their superimposition.

4.2 ANALYSIS OF MILITARY OPERATIONS

Campaigns are composed of a series of related operations. Since no two operations are exactly the same, the numbers of types of operations are infinite. Because of this variability and also because of the complexity of an operation, it is not feasible to determine communication requirements for such a major action directly.

An operation, however, can be broken down into a series of smaller and smaller actions until a finite set of such actions are developed. Each of these small actions would have its own distinct set of needlines. These basic actions will be called "activities." An activity is therefore a military action that has a distinct set of

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communication requirements. Examples of such activities are helicopter evacuation of wounded, artillery general support, engineer bridging support, helicopter gun-ship support, ammunition resupply, and motor transportation support.

The entire set of communication requirements need not be employed in each application of that activity, but a discreet set of requirements can describe the sum total of all such applications. In other words, different applications of a given activity can be different subsets of a set of requirements that are unique to that activity (Figure 4-1).
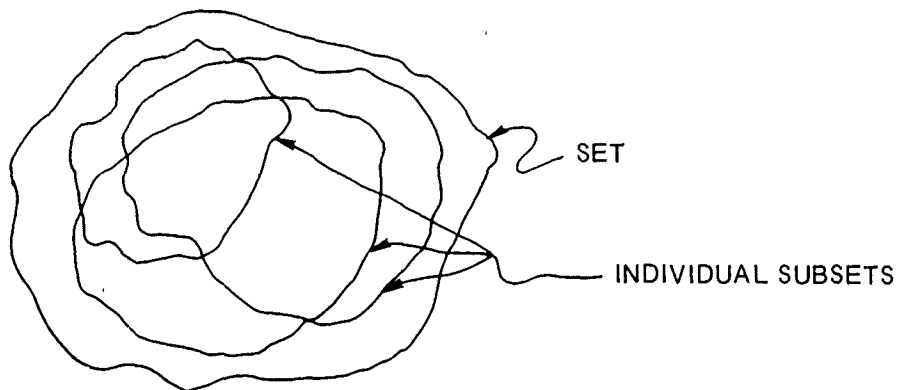
Figure 4-1. Communication Requirement Set Structure

Also, while each activity has a unique set of requirements, individual requirements may be a part of more than one activity set (Figure 4-2).

These activities with their distinct set of requirements therefore become the basic building blocks that can be used to construct any operation. Once the time distribution of activities in an operation is known and the communication needs of each activity have been determined, the requirements of that operation can be derived.

Therefore, in war gaming an operation, it is only necessary to determine what activities are brought into play and when each activity is initiated. For example, we might analyze a campaign by an independent corps. One particular operation might be to sweep and secure a particular area. A division or brigade mission might be to advance to a certain river, hold, and prepare to advance. One task

within that mission might be to neutralize some enemy strong point. The activities are then the basic actions required to accomplish that task. An entire campaign can thus be broken down into a number of engagements, missions, tasks, and, finally, activities. Such an operational break-down is shown in Figure 4-3.

ACTIVITY SET #1

ACTIVITY SET #2

ACTIVITY
SET #4
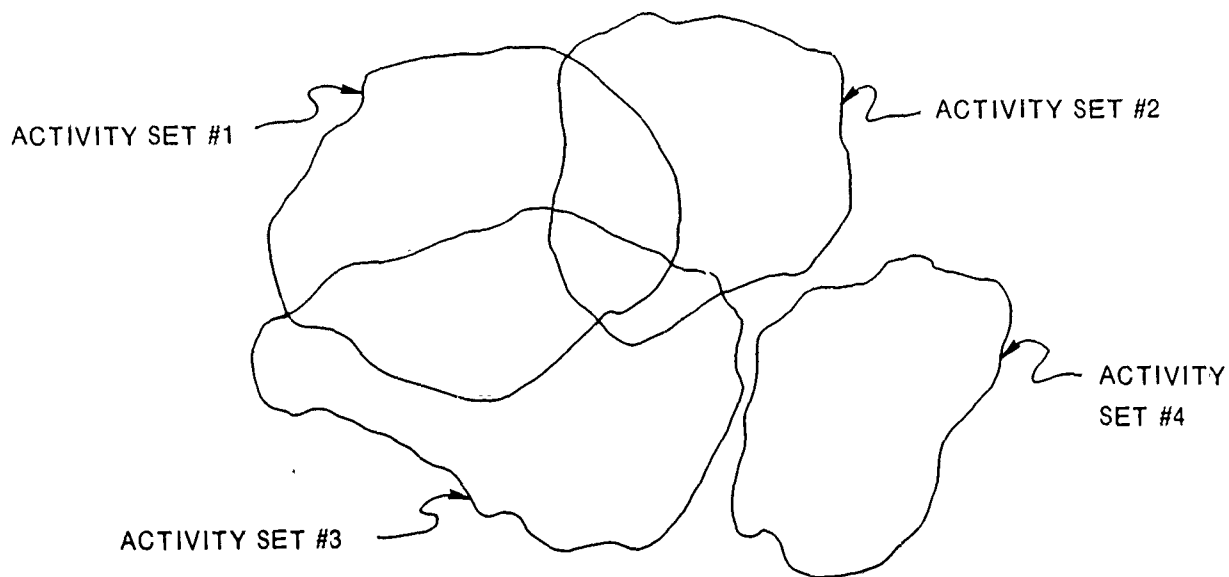
ACTIVITY SET #3

Figure 4-2. Activity Set Interrelationships

A convenient way of accomplishing this analysis is by means of a series of matrices. In the analysis of the campaign scenario, the individual operations would be identified and the time period for each would be noted (Figure 4-4).

	Operations		
	A	B	C
Campaign 1	0600 D 1625 D+4	2200 D+6 2300 D+8	0800 D+12 0200 D+17

Figure 4-4. Campaign-Operation Matrix

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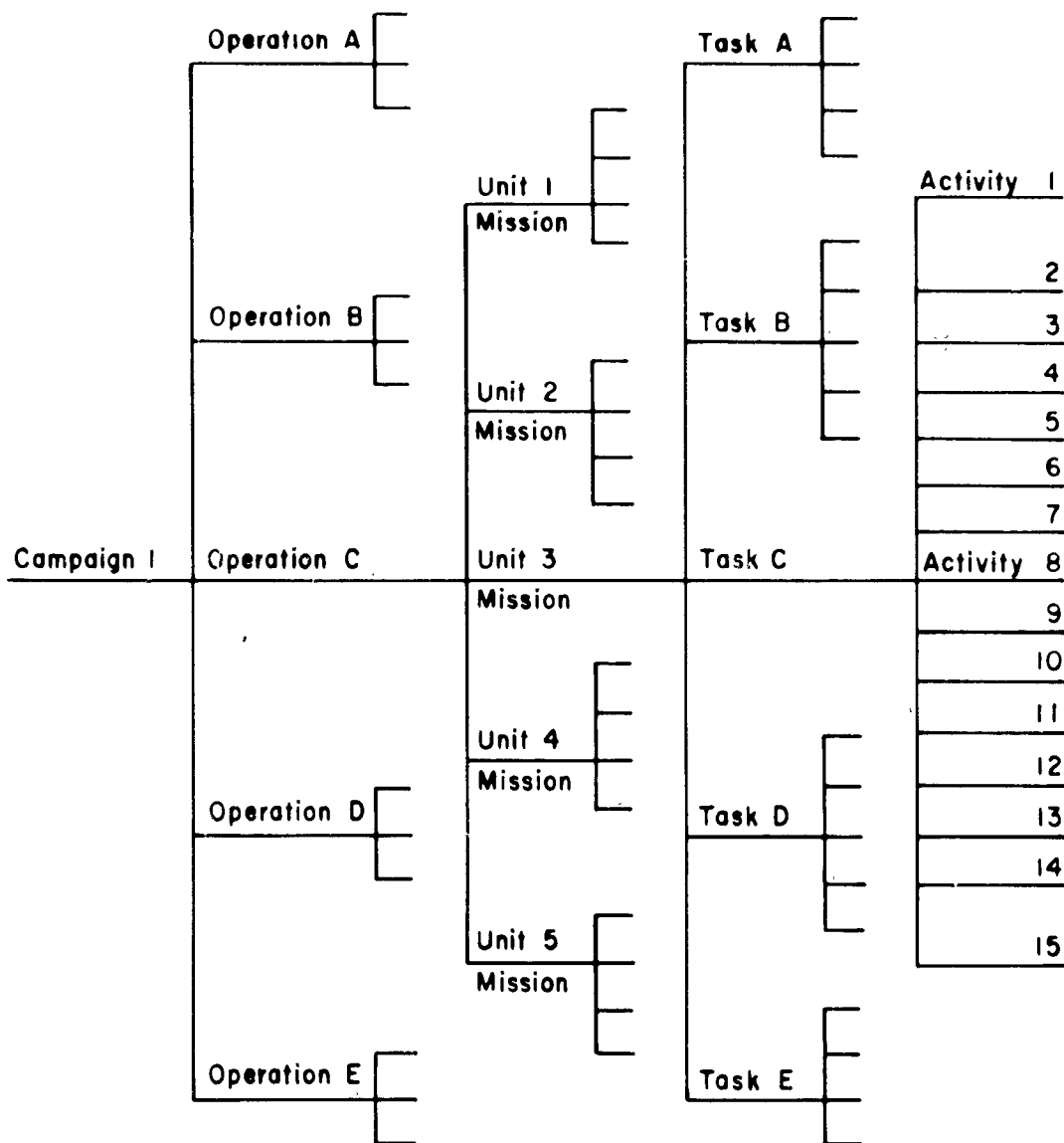
Figure 4-3. Operational Breakdown

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The missions of each of the major elements in the force would then be identified and the time period for each mission would be noted (Figure 4-5). A separate matrix would be generated for each major element or unit.

	Unit Missions			
	1	2	3	4
Operation A	0800 D 0200 D+2	1100 D+1 2300 D+2		
Operation B	0200 D+7 2300 D+8			0700 0400
Operation C			0800 D+2	

Figure 4-5. Operation-Mission Matrix

The next step would be to identify the tasks involved in the accomplishment of each mission and the time periods of their occurrence (Figure 4-6). Here again there will be a separate matrix for each operation of each major element or unit.

	Operation A - Unit 10			
	TASKS			
	A	B	C	D
Mission 1	0800 D 1900 D	900 D 1100 D+1	1930 D 2200 D+1	2200 2300
Mission 2	1100 D+1 1600 D+1		2300 D+1 0300 D+2	
Mission 3				

Figure 4-6. Mission-Task Matrix

In showing the distribution of activities within tasks, a separate matrix is required for each mission of each unit (Figure 4-7).

	Activities			
	1	2	3	4
Task A	0800 D 1130 D	0815 D 1300 D	0900 D 1300 D	1100 1500
Task B	1100 D 1230 D			
Task C			2300 D 0130 D+1	

Figure 4-7. Task-Activity Matrix

Eventually, this analysis operation could be computerized. In fact, there is a possibility that the Ground Combat Communication Simulation Model at the Federal Building in Kansas City might be usable or adaptable to this service. The output of the computer would be a time distribution of activities for a number of different operations.

4.3 DEVELOPMENT OF COMMUNICATION REQUIREMENTS

At this point, the list of activities involved in the operation will have been defined and the time intervals in which each activity takes place will have been determined. The next step is to develop the communication associated with each of the many types of activities.

A Westinghouse study has defined 28 tactical functions and developed the communications associated with each (the term "tactical function" appears to mean the same as "activity"). Some of the tactical function message charts contain all the information needed in this study. Charts for tactical functions 14 and 22 are good examples and are appended.* To implement this concept, such charts would be required for all activites. This information could be

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*Appendices B and C.

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displayed in a matrix form that showed the traffic information for each transmission of each activity.

The traffic information displayed in each box of the matrix would be time, origin, destination, type of traffic, perishability or precedence, and intended circuit (if known).

The time is the time interval between the time the activity is initiated and the time this transmission is initiated. The expression T + 39 means 39 minutes after initiation of the activity. The origin is the unit from which the call is placed. The destination is the unit being called. This "from-to" information constitutes a needline. Three types of traffic will be considered. Anything that occupies a voice channel will be designated TP for telephone. Teletype traffic will be denoted by TT and data traffic will be marked D. The amount of traffic is given in call-minutes for TP, character groups or words for TT, and bits for data. Perishability is the time within which the intelligence must be transferred if the activity is to be considered successful. It is therefore the maximum delay that can be tolerated if the activity is not to abort. If the actual perishability is not known, a value can be assigned based on the precedence of the transmission.

There are two different types of circuits in the Army tactical communication complex. One type provides a multichannel switchable service, while the other takes the form of radio nets that usually operate on a party line basis. Where a needline is normally serviced by one of these radio nets, the actual net must be identified. Otherwise an S is entered to indicate the switchable facility. If, as happens in a few cases, a needline is serviced by both type facilities, both designations shall be shown.

The actual activity traffic data matrix would take the form shown in Figure 4-8. This constitutes the basic requirement data file.

4.4 RADIO NETS

This basic data would be sorted in a number of ways. One sort would be by radio net (Figure 4-9). There are several good sources of information on these radio nets. The appropriate service schools have books that identify these nets for their service and others may also exist. In addition the Bell Aero System Corp at Tucson, Arizona,

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has information on time distribution of radio net require-
ments. These were developed in connection with their self-
interference studies on the environmental test range in
Arizona. A sort on the regiment command net (RC net) might
yield the information contained in Figure 4-9.

Activity Traffic Data			
	Transmission		
ACTIVITY	1	2	3
1	T + 0 Hq B Syn. 17/21 Lancers RHQ 17/21 Lancers TP 2 min Immediate RC Net	T + 3 RHQ 17/21 Lancers Heli 17/21 Lancers TP 2 min Immediate RC Net	
2	T + 0 B Coy R. Anglion Bn Hq 2R Anglion TP 1 min Immediate Bn Net Radio	T + 2 Bn Hq 2R Anglion 19 Bde Hq (G Staff) TP 2 min Immediate Bde C Net	
3			

Figure 4-8. Activity Traffic Data Matrix

Regimental Command Net					
	Transmission				
Activity	1	2	3	4	5
1	T + 0 TP 2 min Immediate	T + 3 TP 2 min Immediate			T + 59 TP 2 min Routine
3	T + 0 TP 5 min Priority		T + 17 TP 3 min Priority		

Figure 4-9. Radio Net Matrix

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This would show that activites 2 and 4 had no traffic
for the radio net. In activity 1, the third and fourth
transmissions did not involve the RC net, et cetera.

Knowing the relative starting times of activities 1, 3,
4, et cetera, will permit a time distribution of traffic
over this net to be obtained. The relative starting times
can be obtained from the set of activity-task matrices
(Figure 4-7).

Since there are no well-founded figures on the rela-
tion between busy period and average daily traffic in these
radio nets, this ratio will have to be developed. In com-
mercial practice, the busy period is taken as one hour. The
validity of using this value or that of some shorter or
longer period will have to be determined in the operation
phase. This busy period may even have to be a function of
precedence. For each radio net it will therefore be neces-
sary to obtain a time distribution of traffic for all
activities having a requirement satisfied by that net.

The next step in the analysis program would therefore
be the preparation of a series of matrices that show the
time distribution of traffic in each radio net over 24 hour
periods (Figure 4-10). In these matrices, time would be
divided into discreet periods of 10 or 15 minutes. The
information contained in each box would include the type of
traffic, the amount in that particular time interval, and
its perishability or precedence.

D+3								
	0000	0010	0020	0030	0040	0050	0100	0110
Radio Net "N"					TP 3 min Immed.			TP 2 min Routine
						TT 1 min flash		TP+D 2 min priority
								TT 1 min routine

Figure 4-10. Traffic Distribution Matrix

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In radio nets, teletype or data traffic always occupies a voice channel. The message length and transmission rate can therefore be converted to a holding time and handled in the same way as voice traffic with respect to channel loading.

The objective of this matrix is to determine the average daily and busy period traffic in each radio net for each type of traffic and each precedence. This information can be developed through a series of sorts of the information in Figure 4-10.

From this data, a histogram (Figure 4-11) of traffic in call-minutes as a function of precedence or perishability can be constructed for each radio net.

4.5 MULTICHANNEL SWITCHABLE SYSTEMS

The multichannel switchable (MS) systems include such items as the Army Area Communication System (AACOM), the Corps/Army Command System, the Division Communication System, and the Adaptive RADA System. While the radio nets were a number of independent elementary networks, the MS system is a complex interwoven network. To resolve this problem, the following general information is needed:

a. The traffic entering and leaving each node

(1) type

(2) amount

(3) precedence

(4) time distribution

b. Network connectivity

c. Routing doctrine

The first step would be to deploy the forces used in the operation under analysis as given by the operation scenario. Then, the communication network of each candidate solution in turn would be superimposed on this deployment. From this force deployment and each of the network overlays, the nodes servicing each unit would be identified. The networks on these overlays will usually be composed of more than one MS system. Interface points between MS systems should therefore be noted.

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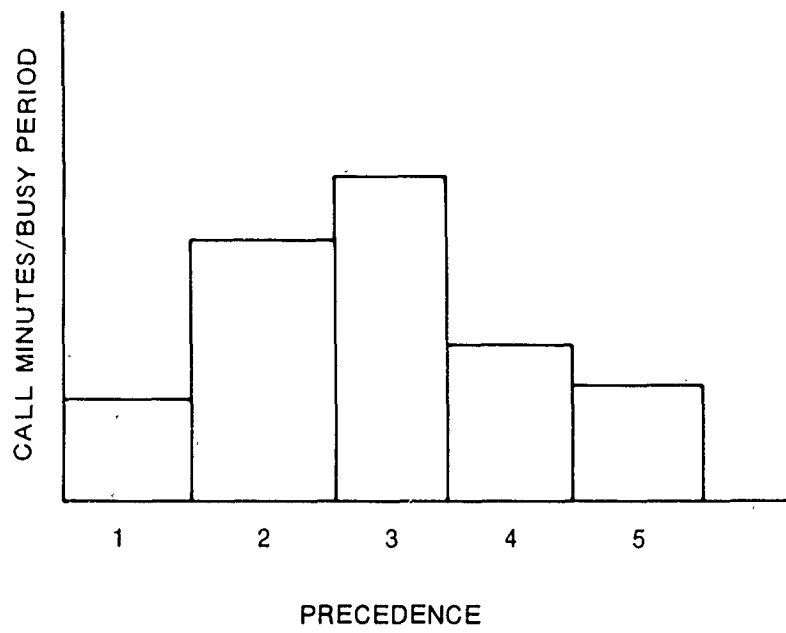
Figure 4-11.   Radio Net Traffic Histogram

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The basic information needed to exercise the evaluation model is the traffic flow between nodal pairs. This information is needed by type of communication and by precedence within types. The specific data required is the busy period traffic and the number of calls entering each nodal pair by node.

To accomplish this, the first sort would be to eliminate all traffic occurring solely in radio nets. This would be a sort of S or multichannel switchable traffic. The information presented will be identical to that shown in Figure 4-8 with the last line (circuit information) deleted. The next sort would be by originator. We have now isolated all the MS traffic originated by a particular unit for each activity and the vital statistics of each, transmission by transmission (Figure 4-12).

Traffic Originated by Unit 4193			
	Transmission		
Activity	1	2	3
1	T+0 1769 TP-2-2		
2			T_2+6 2436 TP-3-1
3		T_3+5 1091 TP-1-1	
4			

Figure 4-12. Unit-Originated Traffic Matrix

Identification of activities involved in tasks and their relative starting times can be obtained from the task-activity matrices (Figure 4-7). By means of the task-mission and mission-operation matrices (Figures 4-5 and 4-6) a complete picture of the time distribution of activities of a particular operation can be developed. Knowing what transmissions are originated by the particular unit under

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analysis, their relative time of initiation with respect to each activity, and the time distribution of activities, we can develop the time distribution of transmissions from that source. This information is displayed in Figure 4-13.

TIME DISTRIBUTION OF TRAFFIC FROM UNIT 4193 ON D+7					
0000	0015	0030	0045	0100	0115
1769 TP-2-2	1091 TP-1-1	2313 TT-200-2	3341 TP-1-1		TT-500-4
2436 TP-3-1	1924 D-800-2	1492 TP-5-3			
2634 TP-4-2					

Figure 4-13. Time Distribution of Transmission Matrix

There would be a separate matrix for each 24-hour period, node and operation. The 24-hour period would be broken into many smaller intervals of 10 or 15 minutes. In these figures, the four-digit numbers such as 1769 or 1091 are unit designations for the called units. TP-2-2 indi-cates two call-minutes of telephone traffic of second level precedence. TT-200-2 indicates 200 character groups of teletype traffic of second level precedence. D-800-2 indi-cates 800 bits of data of second level precedence. If both TP and TT, or TP and D are entered under a single user des-ignator, it would indicate a voice + teletype or voice + data type transmission.

By doing this for each unit serviced by a particular node, the time distribution of traffic entering that node is derived. This can be expressed in matrix form as shown in Figure 4-14. For this figure, the unit designator in the Originating Unit Code column (e.g., 4193) is the calling unit. Those within the individual time boxes (e.g. 1769 and 2346) are the called units.

This information can be sorted by type of traffic and by precedence levels to obtain individual time distributions. The time of occurrence of busy periods and the busy period to average daily traffic ratios for these different traffic types and precedence levels can be determined.

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TIME DISTRIBUTION OF TRAFFIC AT NODE D

Originating Unit Code	D + 7					
	0000	0015	0030	0045	0100	0115
4193	1769 TP-2-2 2346 TT-150-1	1717 TP-5-3 3412 TP-1-1 2241 D-800-2	2346 TT-75-1	2937 TP-3-2 1769 TT-200-1	1414 TP-2-1 3663 TP-2-1 3147 TP-2-1 2193 TT-300-3	1969 TP-4-4 2456 D-900-3
3417						
1492						

Figure 4-14. Time Distribution of Traffic Entering a Node

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TIME DISTRIBUTION OF TRAFFIC AT NODE D							
	D + 7						
Exiting Node	0000	0015	0030	0045	0100	0115	0130
A	TP-6-1 10-2 7-3 6-4 6-5 TT-400-2 D-400-2						
B	TP-4-1 8-3 6-5 TT-150-1 200-3 D-100-1						

Figure 4-15. Time Distribution of Traffic From a Node

4.6 SUPERIMPOSITION OF REPETITIVE AND IRREGULAR TRAFFIC

Early in this section, Army tactical communication traffic was divided into two broad categories: repetitive and irregular traffic. This was done simply as a convenience, since the two types of traffic involved different data-gathering techniques. The evaluation model treats both types identically the same.

To permit the irregular traffic to be superimposed on the repetitive traffic, both must be expressed in the same units. Time, in the case of the irregular traffic, was expressed in minutes after initiation of an activity (see Figure 4-8). In the case of the repetitive traffic, time is expressed in absolute numbers, such as D + 0300 or D + 2 + 1700. Otherwise, the same data is required in both cases.

Since time in the repetitive case is absolute, the basic information can be displayed directly as a time distribution for each 24-hour period. The legend is the same as used in the irregular traffic analysis. The upper left box reads "from unit designator 1414 to unit designator 2171, teletype traffic of 600-character groups carrying a 4th level precedence over the multichannel switchable system".

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The information contained in Figure 4-14 would first be divided into a series of matrices, one for each exiting node based on the unit designators serviced by each node. Each matrix would appear similar to Figure 4-14 except that only the traffic represented by unit designators that exit at the particular node would be shown in each case. There would therefore be a separate matrix for each nodal pair showing the time distribution of traffic between that pair by destination, and type, amount, and precedence of traffic. Each time period is then summed to determine the total amount of traffic and precedence. The result is a time distribution of traffic from each node to every other node by type of traffic and perishability or precedence. One such matrix is depicted in Figure 4-15. Processing of this data will reveal the average daily and busy-hour traffic figures needed.

The number of calls initiated during the busy period, by type and precedence of traffic, can also be derived from Figure 4-14. Since this matrix shows all calls, those originating during the statistically derived busy period can be counted on a node-by-node basis. The three pieces of information needed to derive this count are the busy period, the originating units serviced by each node, and the destination units serviced by each node.

If the traffic characteristics at each node of the MS systems under evaluation and the network connectivity are known, the remaining information needed is the logic or doctrine to be employed in routing each piece of traffic to the called party.

There are two basic routing techniques: deterministic and nondeterministic routing. In deterministic routing, prescribed primary, secondary, tertiary, etc., routes are specified between all nodal pairs. Traffic between these nodal pairs will therefore always follow one of these prescribed routes. In nondeterministic routing, the system will always route the traffic over the shortest route available, whatever that route may be. In this case, the system itself determines the routing for each call. In actual practice, a third routing technique could be employed that is a combination of deterministic and nondeterministic methods. In exercising the evaluation model, the routing doctrine employed would have to be that of the particular candidate solution under analysis.

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D + 3					
0000	0015	0030	0045	0010	01
1414 2171 TT-600-4 S	2424 1179 TP-8-5 S				
2344 2196 TT-900-4 S	1347 2262 TP-4-3 BC Net				
2946 1313 TP-5-3 S	1919 2017 D-9000-2 S				
3156	2491 2419				

Figure 4-16. Repetitive Traffic Data Matrix

The first step is to separate the radio net repetitive traffic from that employing the MS system. This is done by sorting out those boxes having an S entry. Radio net traffic is further sorted by net. Next a series of sorts by origi-nators are made to group traffic by originator. A time distribution of traffic for each node is then developed by grouping traffic statistics for those originating units served by that node. The result is a matrix similar to Figure 4-14.

The information presented in Figure 4-14 would be pro-cessed in the same manner as described for the irregular traffic. The end result would be a time distribution of all repetitive traffic by type, amount, and precedence for each nodal pair. This traffic can now be added by type, precedence, and time period to that developed under the ir-regular traffic analysis.

SECTION 5

QUANTITATIVE RELATIONSHIPS BETWEEN CRITERIA AND ASSOCIATED PERFORMANCE FACTORS

The performance factors and effectiveness criteria listed in Section 3 must now be converted to a suitable input format for the integrated system effectiveness model. This is accomplished in this section by a series of analytic or quantitative relationships between performance factors, criteria, and the measures of effectiveness. These can be described in effect as submodels or effectiveness criteria models. The effect of all performance factors and criteria will be converted to some form of the following:

    a. Traffic load and configuration
    b. Holding time or message length
    c. Allowed delay or perishability
    d. Operating procedures, routing
    e. Redundant traffic resulting from poor quality
    f. Fictitious down-time traffic resulting from unavailability of the system for any reason.

5.1 RELIABILITY AND AVAILABILITY

For the series of criteria such as reliability, availability, maintainability, and survivability, the effectiveness model will actually incorporate the more elementary factor rather than the criteria. For the model operation we use a fictitious down-time traffic when the system is not available. To determine this down-time traffic we need to know the Mean Time Before Failure (MTBF) and the Mean Time To Repair (MTTR). Since there may not always be a direct correspondence of the available data and the level of detail in the model, we may need to compute a composite MTBF and MTTR. The following formulas describe the methods for computing composite reliability and availability values and hence conversely of computing a composite MTBF and MTTR.

A substantial amount of work has been done during the past 15 years in the development of analytical means to determine the reliability of a system under varying conditions. This work has led to numerous mathematical expressions covering such items as network configuration, ability to repair failed units, failure and repair rate distributions, et cetera. A number of rule of thumb assumptions have evolved through correlation of theory and field data.

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The mathematical expressions given below are based on these assumptions. Before proceeding to the actual equations, it is important that the assumptions are stated:

a. The failure and repair rates are assumed to be constant, hence resulting in exponential probability distributions.

b. For networks which have repairmen available for work on failed units, the number of such repairmen is assumed to be equal to the total number of system units.

c. Units which are in a standby mode awaiting use when an on-line unit has failed are assumed to have a failure rate of zero while in the standby mode.

It is proper to categorize the reliability equations into two classes: non-repairable systems and repairable systems. It should be obvious that the latter class is the much more complicated class and the equations that follow clearly indicate this fact.

a. Non-Repairable Systems

1. Single Unit System:
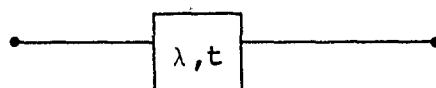
$$R(t) = e^{-\lambda t} \qquad (5\text{-}1)$$

where $R(t)$ = Reliability up to time t

λ = Constant system failure rate = $\dfrac{1}{\text{MTBF}}$

t = Mission time

MTBF = Mean time between failures

2. Series Arrangement of N Units:

$$R(t) = e^{-(\lambda_1 + \lambda_2 + \lambda_3 + \ldots\ldots + \lambda_n)t} \qquad (5\text{-}2)$$

For the special case where all units are identical we have

$$R(t) = e^{-n\lambda_1 t} \qquad (5\text{-}3)$$

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3. Parallel Arrangement of N Units:
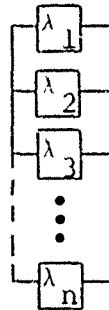
$$R(t) = 1 - [(1-e^{-\lambda_1 t})(1-e^{-\lambda_2 t})(1-e^{-\lambda_3 t})\ldots\ldots(1-e^{-\lambda_n t})] \quad (5\text{-}4)$$

For the special case where all units are identical we have

$$R(t) = 1 - (1 - e^{-\lambda_1 t})^n \quad (5\text{-}5)$$

4. Series-Parallel Arrangement of Units:
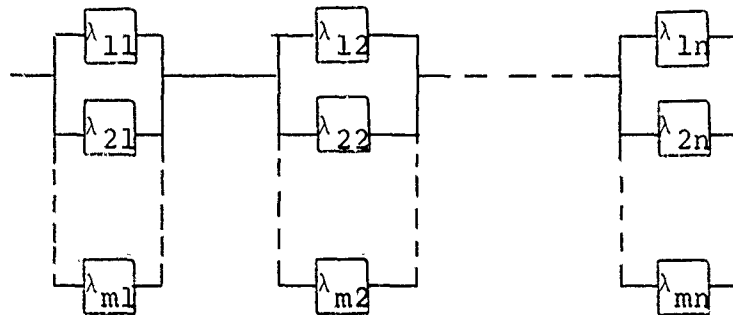
$$R(t) = \prod_{j=1}^{n}\left\{ 1 - \prod_{i=1}^{m}(1 - e^{-\lambda_{ij} t}) \right\} \quad (5\text{-}6)$$

5. Non-Series Parallel Arrangement of Units:

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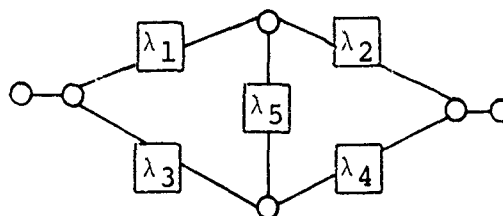
$$R(t) = e-\lambda 5t[R(t) \backslash 5=0] + (1-e-\lambda 5t)[R(t) \backslash 5=\infty] \qquad (5-7)$$

Equation 5-7 is somewhat more involved than the equations for the more conventional network arrangements presented previously. This equation states that the reliability of the system is equal to the reliability of unit 5 times the reliability of the remaining network with unit 5 short-circuited (i.e., $\lambda_5=0$) plus the unreliability of unit 5 times the reliability of the remaining network with unit 5 open-circuited (i.e., $\lambda_5=\infty$). The effect of Equation 5-7 is to reduce the non-series-parallel network to series-parallel form by operating on the unit which converts the network from one form to the other. Once the network is in series-parallel form, Equation 5-6 can be employed to determine the overall reliability. Equation 5-7 is the expression for the simplest non-series-parallel network, the well-known bridge network. In general, the networks of this type are much more complicated. The use of the Factoring Theorem of Boolean Algebra as applied to reliability networks by Weinstock[13], however, can be used in an iterative manner to reduce any network to series-parallel form by operating on individual units one at a time. The major difficulty with the technique is the ability to choose those units which affect the network reduction in the most efficient manner. In the bridge network above the choice was obvious, but in more complex networks it is extremely difficult to ascertain which are critical units for producing the least number of iterations resulting in a set of series-parallel sub-networks.

b. Repairable Systems

1. Single Unit System: By definition, the reliability of a system is the probability of its not failing within a stated mission time t. Repairmen are used to increase the probability that a system will not fail. In the case of a single unit, system repairability has no meaning or effect on the reliability of the system since a repairman cannot prevent the system from failing. Once it fails, he can then repair it and restore it to service. This failure and repair process can occur many times during a mission period, but the figure merit that evaluates this effect on system success is denoted as availability and will be covered in detail later.

2. <u>Parallel Unit System:</u>
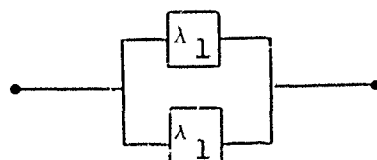
One repairman, both units identical

$$R(t) = \frac{S_1 e^{S_2 t} - S_2 e^{S_1 t}}{S_1 - S_2} \qquad (5-8)$$

where

$$S_1 = \frac{-(2\lambda + \mu) + \sqrt{\mu^2 + 6\lambda\mu + \lambda^2}}{2}$$

$$S_2 = \frac{-(3\lambda + \mu) - \sqrt{\mu^2 + 6\lambda\mu + \lambda^2}}{2}$$

and

$$\mu = \text{repair rate} = \frac{1}{MTTR}$$

MTTR = Mean Time to Repair

It is clear from this simple, two identical unit parallel system that the reliability expression is far more complex than for the non-repair case. On the other hand, the reliability of the repairable system is clearly much greater since when one unit fails it can be repaired so that when the second fails the first will be operating and the system still will be reliable. In this case a failure of the system can only occur if the second unit fails within the repair period of the first unit. As the number of units in parallel is increased, the mathematics become extremely complicated and are beyond the scope of what is intended in this study.

3. <u>Standby Redundancy System</u>: Another way to effect increased reliability, when repairability is available, is through use of standby units that are put into operation in the event of failures in operational units. In this manner systems which require that one or more on-line (operational) units must be working for system success can

be kept reliable by the addition of standby units. The simplest example of this type of system is a two-unit system with one unit in operation, one unit in standby, and one repairman available. For this system the reliability equation is as follows:

$$R(t) = \frac{S_2 e^{S_1 t} - S_1 e^{S_2 t}}{S_1 - S_2} \tag{5-9}$$

where

$$S_1 = \frac{-(2\lambda + \mu) + \sqrt{\mu^2 + 4\lambda\mu}}{2}$$

$$S_2 = \frac{-(2\lambda + \mu) - \sqrt{\mu^2 + 4\lambda\mu}}{2}$$

Once again the mathematics to determine the reliability of a system which requires m out of k on-line units to be working and has 1 off-line unit in standby with $n = 1 + m$ repairmen available are extremely complicated and lengthy and serve no purpose in relation to the study in hand.

Of importance, however, to the prosecution of the present study are the expressions for the Mean Time Between Failures (MTBF) for non-repairable systems and the Mean Time to First Failure (MTTF) for repairable systems. Table 5-1 lists the MTBF's and MTTF's for the two classes of reliability systems. The significance of these parameters will become more obvious in the next section when the basis for the effectiveness model is described in detail.

5.2 MAINTAINABILITY

Maintainability is concerned with servicing techniques which will result in minimizing system down-time over a specified period of operation. In this sense maintainability is directly related to reliability and availability. The most general description corresponds to the steady state availability (A) expression for a single unit system:

$$A = \frac{\text{Up Time}}{\text{Up Time + Down Time}} = \frac{\text{MTBF}}{\text{MTBF + MTTR}}$$

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TABLE 5-1. MTBF's AND MTTF's FOR RELIABILITY SYSTEMS

Reliability Class	Configuration	MTBF or MTTF Expression
Non-Repairable	Single Unit	$MTBF = 1/\lambda$
	Parallel Redundancy - n Identical Units	$MTBF = 1/\lambda \sum_{i=1}^{n} \frac{1}{i}$
	Series Redundancy - n Units	$MTBF = 1/ \sum_{i=1}^{n} \lambda 1$
Repairable	Parallel Redundancy - n Identical Units, n repairmen	$MTTF = \frac{1}{\lambda} \sum_{k=0}^{n-1} \frac{(1 + \mu/\lambda)^k}{k+1}$
	Standby Redundancy - n Identical Units, n-1 in standby, n-1 repairmen	$MTTF = \frac{1}{\lambda} \sum_{k=0}^{n-1} \frac{n!}{(k+1)(nkh)} \left(\frac{\mu}{\lambda}\right)^k$

Down-time is the term for which maintainability techniques are sought, since it is the term associated with the system not being in the operating state.

There are a number of factors governing the down-time period of a system. One is scheduled maintainence which finds application largely in those cases where the system is not operating continuously and the maintenance tests can take place in off hours. Another cause of down-time is insufficient spare parts on hand. The major cause of system down-time, however, is due to non-scheduled maintenance which is the result of catastrophic failures. The emphasis therefore is to develop methods of rapidly restoring systems to service after unscheduled failures. The parameter which is most often used to describe maintainability is Mean Time to Repair (MTTR). MTTR is inversely proportioned to the repair rate μ.

5.3   TRANSPORTABILITY AND MOBILITY

Although transportability and mobility are two separate criteria, they are both directly time-related and as a result can be treated in a like manner for use with the effectiveness benefit model. Transportability is concerned with the transit time used in moving a system from one location to another. The factors which determine the transit time are size, weight, number and type of vehicles employed, terrain, et cetera. For the purposes of the model, however, only the total time in effecting the transport is needed since it will be considered as down-time traffic from the systems viewpoint.

Mobility, which is closely related to transportability, involves the time to dismantle and reassemble an operational system. The same set of general performance factors impact on mobility as for transportability. As before the only parameter of concern for the model is the overall tear-down and set-up times. Therefore, both transportability and mobility will result in quantitative time periods which can be combined to give an overall system down-time traffic number for insertion into the effectiveness model.

5.4   QUALITY OF SERVICE

The environment in which ECOM communication systems will find themselves dictates the major mediums of information transmission. These media are HF, Troposcatter, and Line-of-Sight (LOS). The following paragraphs attempt to summarize and categorize the quality of service for both analog and

digital communications via the three media utilizing the equipment and techniques known to be available for such transmissions. The purpose of this paragraph is to compute or estimate the amount of redundant traffic that will occur as a result of poor quality or error rate, the capacity of the channels, and down time due to propagation outages.

5.4.1 Troposcatter and LOS

Troposcatter transmission and line-of-sight transmission will be treated together in the ensuing paragraphs since both media are characterized by the same channel model. First we will treat quality of service for analog information transmissions, and then the more complicated case of digital data transmission.

a. Analog Information Transmission

In the case of analog information transfer the figure of merit for quality of service is signal-to-noise ratio (SNR). Due to language redundancy, a substantial portion of voice type transmission is not really considered as information transfer. The other major source of reducing information transfer is noise due to the transmission medium and system equipment characteristics. Analog transmissions and troposcatter channels almost always employ an FM modulation scheme. The following mathematical expression relates signal-to-noise ratio in the voice band (3.1 kHz) to the characteristics of the troposcatter channel.

$$(S/N)_{3.1 \text{ kHz}} = C/N_{RF} \left(\frac{B}{2b}\right)\left(\frac{fd}{fm}\right)^2 D \qquad (5\text{-}10)$$

where

C = Carrier power level

B = RF Bandwidth

b = 3.1 kHz (audio channel)

$N_{RF} = -174 + 10 \log B + R_{NF}$ (R_{NF} = Receiver Noise Figure)

fd = peak frequency deviation

fn = baseband frequency $4N + 60$ kHz (N = # of channels)

D = diversity gain

and

$$C = \frac{P_r \sum G_n}{\sum L}$$

where

P_r = radiated power

G_n = antenna gain characteristics

L = losses due to propagation, scatter (for tropo)
line, receiver noise figure, et cetera

Threshold SNR levels can be set beyond which the information transfer rate is considered to be too low for adequate conversations. In this manner quality of service can be established for analog transmissions over troposcatter and LOS channels.

b.   Digital Information Transmission

The basic measure of digital transmission quality is the probability of bit error expected. In a troposcatter or LOS system there are three possible sources of bit errors that are significant. These are: inter-symbol interferences due to differential time delays in the path, time-selective fading of the received signal, and noise in the presence of the Rayleigh-distributed fluctuations of the carrier. The differential transmission time delays are only of significance for relatively high bit rates and are due to the multipath phenomenon, basically the same that gives rise to frequency selective fading (i.e., correlation bandwidth) limitations in analog transmissions. The second source of bit errors, time selective fading, refers to the fading rate of the received signal with time. However, in troposcatter and LOS propagation, this type of fading is still relatively slow in comparison to data transmission rates and may only be of significance in very low-speed transmissions. The third, and final, source of error is the noise that is present in the data channel. In the troposcatter and LOS UHF band, this is predominantly receiver front-end thermal noise, acting against the Rayleigh-distributed carrier. This latter source of error is largely a function of the system gains and losses - i.e., the received power level.

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It is, of course, immaterial whether the digital informa-
tion to be transmitted presents a high-speed data output
from, say, a computer facility, or several low-speed digital
channels time-division-multiplexed into a single stream.
Nor is it essential to the present considerations if the
basic information is truly data, or pulses derived from
analog channels with .CM or delta modulations. But the
manner and rate of digital transmission are of importance in
determining the expected system performance.

Although numerous digital transmission schemes are pos-
sible, two basic methods are assumed. The first is direct
transmission, where the digital baseband modulates the radio
carrier directly. This system is relatively simple, espe-
cially suitable where predominantly digital information is
to be transmitted. However, in the near future, it is
likely to be more common that relatively small quantities of
digital information are routed through the existing analog
radio telephone FDM-FM plant. Thus, the second method of
digital transmission to be considered is the modulation of a
subcarrier within the analog baseband.

Transmission of rates limited to 38.4 kb/s (occupying
12 channels) or less may be assumed to be feasible through a
wideband analog FDM-FM troposcatter system. Higher rates,
however, would upset the peak loading considerations upon
which the analog baseband design is based and would severely
impair overall system performance. Efficient transmission
of higher speed digital information therefore requires
schemes more specifically amenable to that type of modula-
tion, i.e., direct-carrier modulation. A method of modula-
tion which is practically feasible, and which is assumed
here as representative, is binary differential phase shift
keying (DPSK), which approaches the performance of an ideal
system when error probabilities are relatively low.

The calculation of the approximate error probabilities
for such a scheme draws upon the work of many contributors,
and has been well summarized by Smith.[12] For the digital
transmission system, as a first approximation, the composite
nondiversity probability of error, for direct digital tropo-
scatter transmission, may be given as

$$P_{e,1} \approx P_{e,1}^{(1)} + P_{e,1}^{(2)} + P_{e,1}^{(3)}$$

where

$P_{e,1}$ = composite probability of error (no diversity)

$P_{e,1}^{(1)}$ = probability of error due to the path differential time delay (no diversity)

$P_{e,1}^{(2)}$ = probability of error due to time selective fading (no diversity)

$P_{e,1}^{(3)}$ = probability of error due to random noise in the presence of flat Rayleigh fading (no diversity)

To arrive at the composite, or resultant error probability, the three sources of error must first be evaluated individually.

The 4-fold diversity improvement for post-detection maximal-ratio combining of DPSK carriers, assuming equal fading on all diversity branches, reduces to the expression

$$P_{e,4} = 8(P_{e,1})^4$$

Of the expressions contributing to $P_{e,1}$, the path differential time delay is normally dominant for wideband all-digital systems.

Theoretically, the same potential sources for the occurrence of errors that exist for direct digital transmission exist also for digital transmission within the FDM-FM baseband. Practically, the only error source of concern is threshold model or the abrupt threshold model. In the first model, the output SNR is assumed to drop 2 dB for every 1 dB drop of the input carrier level. In the latter prototype, the output SNR abruptly drops to zero as the RF carrier dips below threshold. These two assumptions represent extremes, with the actual receiver performance ordinarily lying in between.

For the present considerations, the smooth threshold model is not attractive for use. Aside from its inherently optimistic nature, this model could give large variations in error performance with small changes in the received carrier

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level. Since the received carrier level cannot be estimated
to a large degree of accuracy, the results derived could be
very misleading. Moreover, to protect telephone channels
from disagreeable bursts of noise, maximal-ratio baseband
combiners are often designed to cut out of the combining
process any diversity branch in which the carrier drops
below threshold. It is therefore preferable to base our
results on the abrupt threshold model. Although the perform-
ance subsequently derived will be inherently pessimistic, it
represents an upper bound on the error probabilities that
might actually be achieved, and gives the system designer a
cautious framework upon which to base his requirements.

With a zero signal-to-noise below threshold, the proba-
bility of error automatically reduces to 1/2. The average
probability of error with diversity over say, an hour, would
thus be approximated as

$$P_{e,N} = \frac{0.5 \text{ x percent of hour combined signal is below threshold}}{100 \text{ percent}}$$

The effective threshold level, for receivers utilizing
threshold extension circuitry, is assumed to occur at a
carrier-to-noise ratio of 7 dB.

Figure 5-1 presents an example of the type of error
probability versus distance tradeoff indicated by calcula-
tions of the type outlined above. The solid curve is based
on the assumption that 38.4 kb/s of digital data is modu-
lated onto a subcarrier in an FDM-FM system, displacing 12
4-kHz channels. The curve for direct binary DPSK at 192 kb/s
indicates the relative performance of such a system trans-
mitting five times as much data in the same total bandwidth -
i.e., at the same rate per channel. For a 10^{-5} error proba-
bility, the range is seen to be extended by a factor of
nearly two-thirds. It should be remembered that these
results reflect the system performance in the worst 0.1 per-
cent of the time.

A comparison which is probably more meaningful is that
between the FDM-FM curve and the DPSK curve for 2.5 mb/s,
which represents a bit rate, per unit of bandwidth, some 13
times as great. Over the range of P_e from 10^{-3} to 10^{-5} these
two curves are quite close. It is noted that a slight
sacrifice in information rate, so that the ratio of rates
might be only 12:1, say, a modest amount of error-control
coding could easily reduce an error probability of 10^{-3} to

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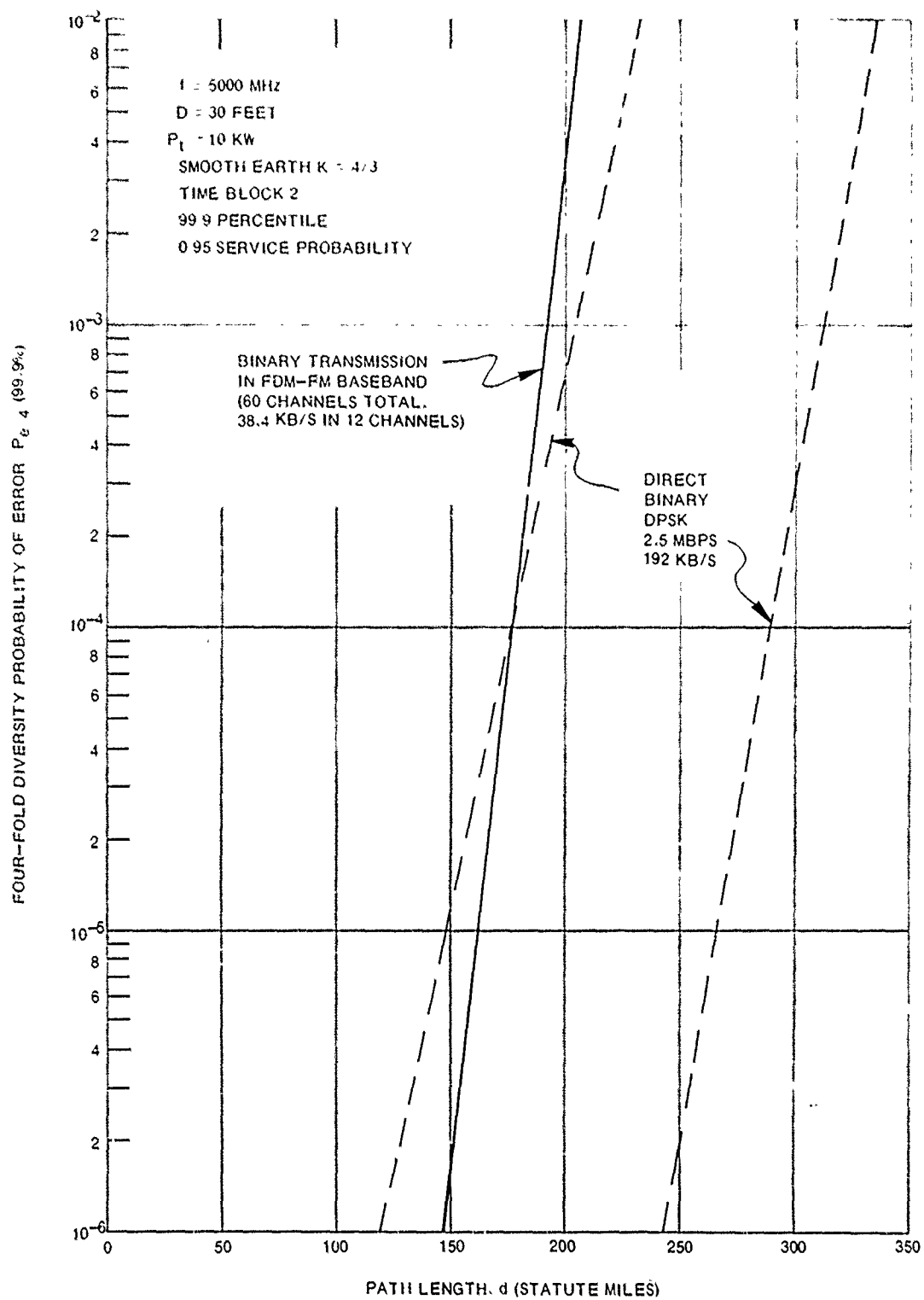
Figure 5-1. Error Probability Versus Distance
Tradeoff

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10^{-5}, making the range of the digital system about 37 percent greater than before, and slightly greater than that of the FDM-FM system used for comparison.

A final comment indicates the sensitivity of the results to the choice of the method of modulation and demodulation. A near-optimum modulation technique for troposcatter has been developed by Levine et al[1], which employs quaternary DPSK with successive bauds sent on alternate frequencies. That is, two frequencies are employed, as in binary FSK, but with a four-phase signal sent alternately on the two frequencies. This approach almost completely eliminates the dominant restriction of intersymbol interference due to multipath spread with resulting great improvement in error performance. A comparison between a conventional 190-nm link employing binary FM and the same link using the optimum modulation yielded error rates of 8.9×10^{-6} and 5.8×10^{-10}, respectively, at 3.8 mb/s. In this case, the modulation rate of the optimum modulator could be increased to 15.2 mb/s and still give an error rate no larger than 0.33×10^{-6} on a 190-nm link.

For LOS and for the class of troposcatter systems where multipath and time selective fading contribute either a negligible amount or nothing to the probability of bit error, a handy reference is provided by Table 5-2. This table gives the probability of bit error with N-fold diversity for the group of diversity-detection schemes that are of practical interest. The only sources of errors assumed is due to noise alone and the various schemes are compared to the ideal coherent PSK maximal-ratio system which is taken as the reference.

5.4.2 Long Haul HF Performance Calculations

  a. Analog Transmission

An extensive number of measurements and electronic computer simulations of HF links have been carried out by the NBS Ref 14, 15 (Adapt. Prop) and other organizations to determine the available median SNR as a function of distance between communication points and the time of day at the midpoint of the communications circuit. The variation in median SNR as a function of distance for sunspot numbers (SSN) of 10 and 100 are given in Figure 5-2. In deriving these cruves, rhombic antennas and a 12-KW PEP transmitter were assumed.

TABLE 5-2. PRACTICAL DETECTION-DIVERSITY SCHEMES
PROBABILITY OF ERROR COMPARISON (BINARY TRANSMISSION) ERRORS
DUE TO NOISE ALONE HIGH SIGNAL-TO-NOISE RATIOS ($\bar{p}$--MEAN SNR OF
NONDIVERSITY RAYLEIGH FADING DISTRIBUTION)
4-FOLD DIVERSITY (N = 4)

Case	Detection	Diversity combining	Probability of error with N-fold Diversity $P_{e,N}$	$P_{e,4}$	For same $P_{e,4}$ Relative Reference system	For same $P_{e,4}$ Required $\bar{p}$ Relative to Reference system, db
I (Reference system)	Ideal coherent PSK	Predetection Maximal ratio	$\frac{(2N-1)!}{N!(N-1)!}\left(\frac{1}{4\bar{p}}\right)^N$ [11]	$0.14\left(\frac{1}{\bar{p}}\right)^4$	1	
II	Coherent PSK with differential decoding	Predetection Maximal ratio	$4\frac{(2N-1)!}{N!(N-1)!}\left(\frac{1}{4\bar{p}}\right)^N$	$0.28\left(\frac{1}{\bar{p}}\right)^4$	2	+0.6
III	DPSK (previous bit used as reference)	Predetection Maximal ratio	$2^n - 1\left(\frac{1}{2\bar{p}}\right)^N$ [ ]	$0.50\left(\frac{1}{\bar{p}}\right)^4$	3.6	+1.4
IV	DPSK (previous bit used as reference)	Predetection equal gain	$4N-1N^n\frac{(N-1)!}{(2N-1)!}$ $\times\left(\frac{1}{2\bar{p}}\right)^N$ [11]	$1.2\left(\frac{1}{\bar{p}}\right)^4$	8.6	+2.5
V	DPSK (previous bit used as reference)	Postdetection equal gain	$\frac{(2N-1)!}{N!(N-1)!}\left(\frac{1}{2\bar{p}}\right)^N$ [11]	$2.2\left(\frac{1}{\bar{p}}\right)^4$	16	+3.5*
VI	Coherent FSK	Predetection maximal ratio	$\frac{(2N-1)!}{N!(N-1)!}\left(\frac{1}{2\bar{p}}\right)^N$ [11]	$2.2\left(\frac{1}{\bar{p}}\right)^4$	16	+3.5*
VII	Incoherent FSK	Predetection maximal ratio	$2^n - 1\left(\frac{1}{\bar{p}}\right)^N$ [5]	$8\left(\frac{1}{\bar{p}}\right)^4$	57	+4.4
VIII	DPSK (previous bit used as reference)	Predetection or postdetection	$2^n - 1N!\left(\frac{1}{2\bar{p}}\right)^N$ [7]	$12\left(\frac{1}{\bar{p}}\right)^4$	86	+4.8
IX	Incoherent FSK	Predetection equal gain	$4^n-1N^n\frac{n(N-1)!}{(2N-1)!}$ $\times\left(\frac{1}{\bar{p}}\right)^N$ [11]	$19.5\left(\frac{1}{\bar{p}}\right)^4$	140	+5.4
X	Incoherent FSK	Postdetection square law equal gain	$\frac{(2N-1)!}{N!(N-1)!}\left(\frac{1}{\bar{p}}\right)^N$ [7]	$35\left(\frac{1}{\bar{p}}\right)^4$	250	+6.0*
XI	Incoherent FSK	Predetection or postdetection selector	$2^n - 1N!\left(\frac{1}{\bar{p}}\right)^N$ [7]	$192\left(\frac{1}{\bar{p}}\right)^4$	1370	+7.9

*Independent of N.

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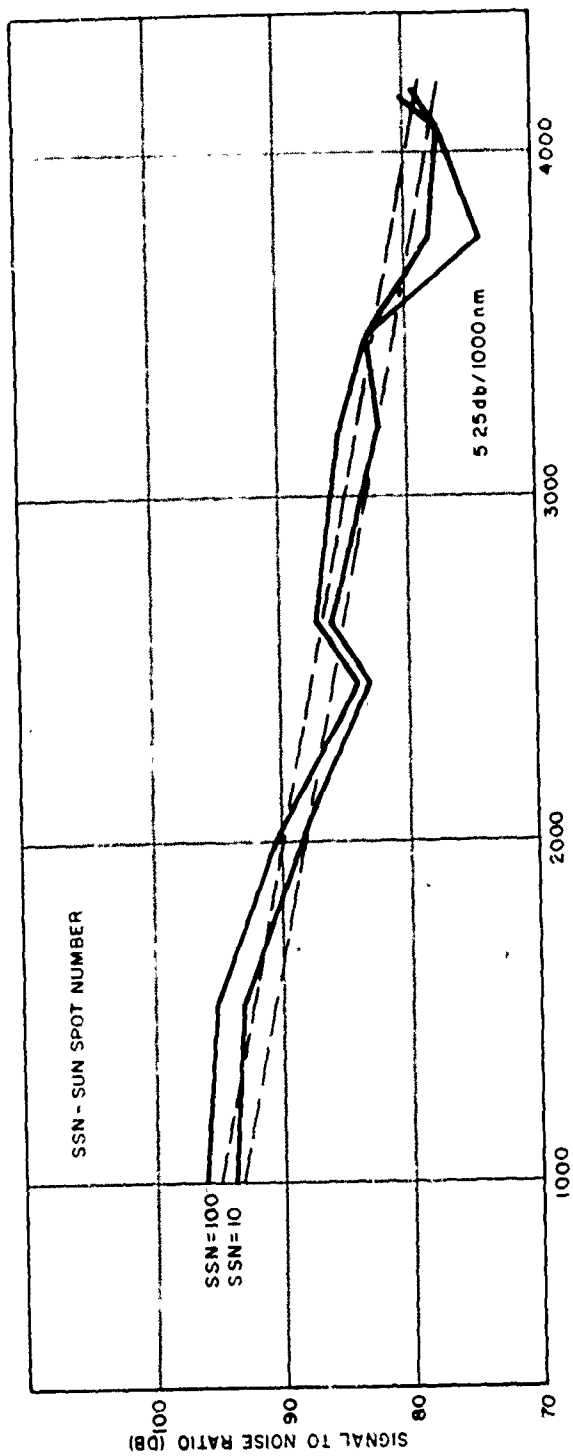
Figure 5-2. Distance (Nautical Miles) Median Signal to Noise Ratio in
a 1-Cycle Band as a Function of Distance

In order to obtain a satisfactory circuit for an appreciable part of the time, it is necessary to use operating frequencies in portions of the HF band that can support transmission at the moment. The situation is illustrated by the diurnal variation, which is shown in Figure 5-3. This figure shows the calculated SNR's to be expected in an average day during which the sunspot number is 10 over a particular path of about 4000 miles in length. A transmitter PEP of 12 KW is assumed. From this figure, it may be seen that beginning at about 0600 GMT, the SNR drops suddenly and soon goes to more than 50 dB below the previous high value. At 1200 GMT, the density of ionization becomes high enough so that a high SNR is obtainable at frequencies in the upper HF band. This drops slowly until local noon on the path, then rises again and continues to be high until about 2200 GMT, when the ionization on the path drops and it is necessary to switch to a lower frequency for the remainder of the night.

HF propagation is also subject to short-term variations that cause fading of the received signal. The rate of the variation ranges from a fraction of a cycle per second to several cycles per second and depends upon the measurement technique used, the characteristics of the path, and the particular propagation conditions existing at the moment. In addition to fading, signals arriving at the receiving antenna over more than one path result in multipath. Since the lengths of the paths are different, the arrival of the signal is spread out over an interval of time. The maximum expected multipath time delay difference, as a function of path length, is illustrated in Figure 5-4. For long path lengths (3000-6000 nm), multipaths of under 4 milliseconds duration predominate.

At HF frequencies, atmospheric and manmade noises are not Gaussian when the noise level is high; hence, the envelope distribution of HF noise departs appreciably from the Rayleigh in this region. It has been found, in fact, that the peak values of atmospheric noise closely follow the log-normal distributions, and it is these peak values that are the primary cause of noise-induced errors.

For normal analog transmissions the information bandwidth of 3 kHz the SNR's depicted in Figures 5-2 and 5-3 are reduced by 35 dB. In the case of four 3-kHz channels multiplexed together the SNR values in Figures 5-2 and 5-3 are reduced by 41 dB. Due to the large degree of unpredictability associated with HF propagations, there are no general equations available to express SNR in terms of the HF

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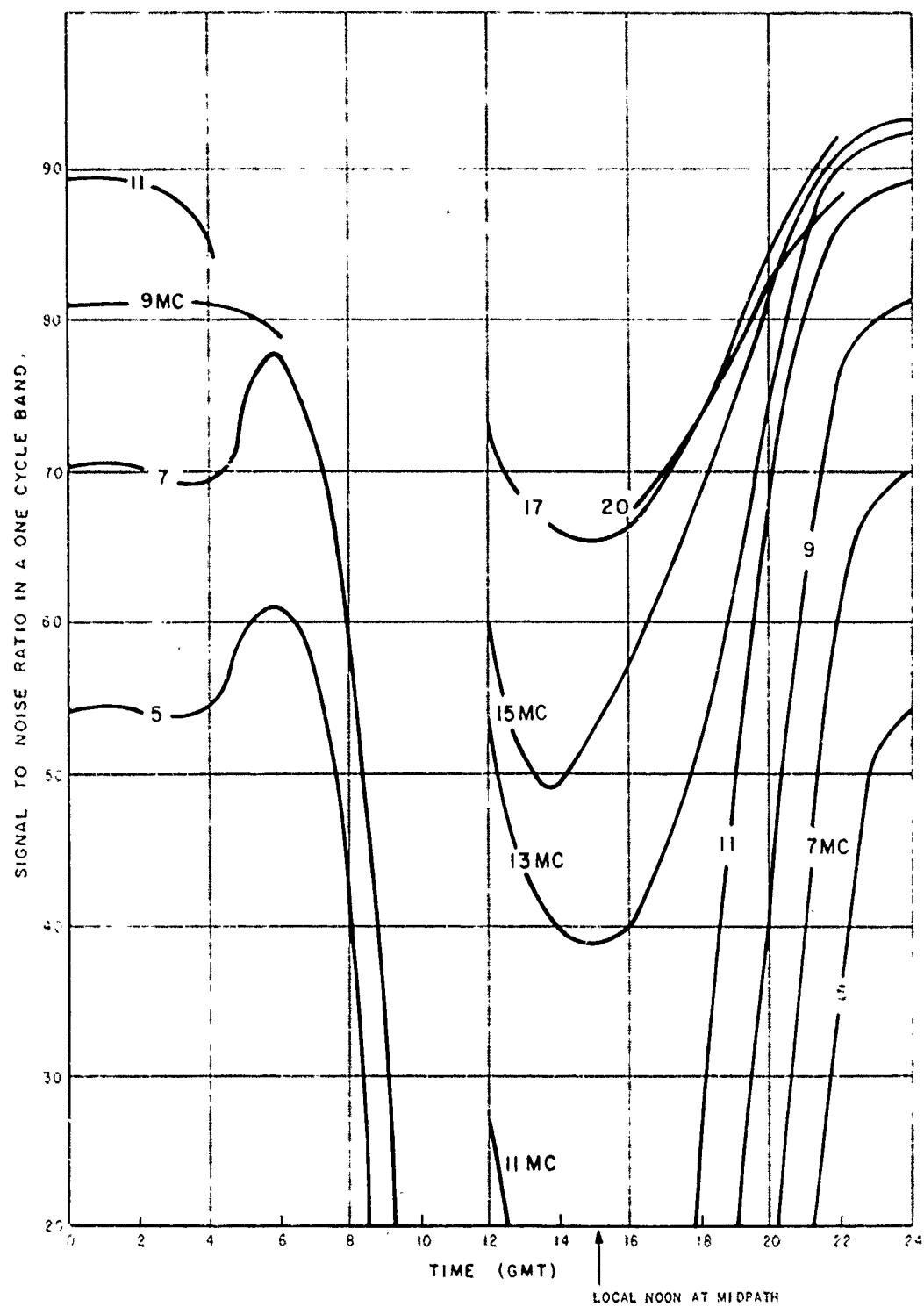
Figure 5-3. Diurnal Variations in a 4000-Mile HF Link

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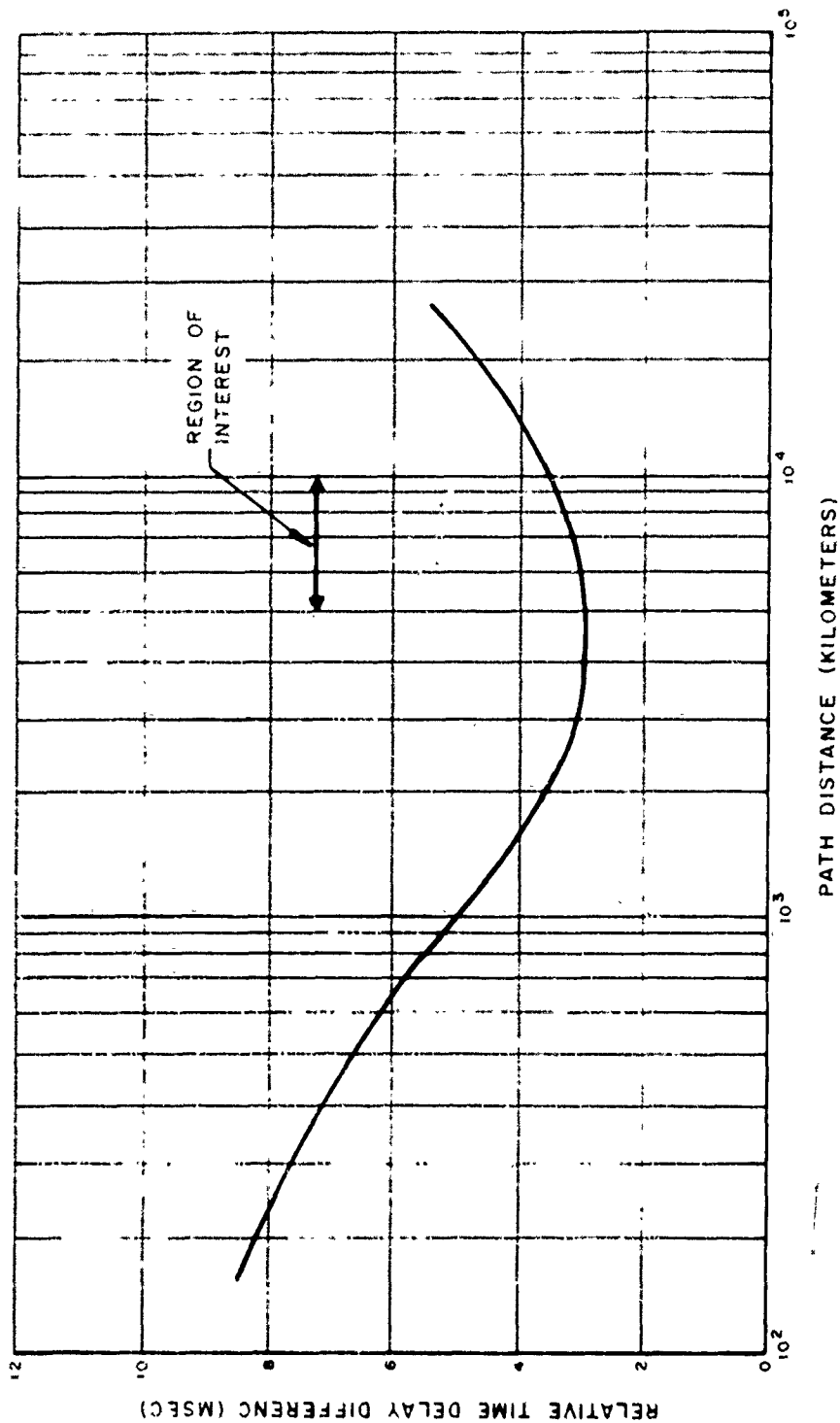
Figure 5-4. Maximum Expected Multipath Time Delay Difference (Point To Point)

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parameters and type of equipment used. It is to be noted, however, that the modulation scheme used in almost all HF systems is independent sideband (IS).

b. Digital Transmission

On the basis of NBS calculations, Curve 1 of Figure 5-5 represents the SNR necessary to obtain the ordinate value of bit error probability in a single 75-baud teletype channel in the presence of atmospheric noise and a Rayleigh fading signal. FSK modulation and incoherent detection are assumed. Curve 2 is included for comparison, and is calculated for Gaussian additive noise and Rayleigh fading. To compare Curve 1 with the SNR in a one-cycle band, plotted in Figure 5-2, it is necessary to include the baud-rate correction factor, thereby obtaining Curve 3 of Figure 5-5, and to reduce the ordinate value in Figure 5-2 by allocating the total transmitter power among the simultaneously transmitted TTY channels. If, instead of one teletype channel, 16 parallel FSK subchannels were transmitted on each of four multiplexed channels under the same PEP restriction, an additional 24 dB in SNR per cycle of bandwidth would be required to maintain the same error probability (18 dB for the increase in data rate and 6 dB for the peak to average power factor). Stated alternately, the available SNR plotted in Figure 5-2 is reduced by 24 dB. Hence, at 4000 nm, the median signal to noise available in a one-cycle band is 78-24-54 dB. Examination of Curve 3 of Figure 5-5 reveals that approximately 67 dB SNR per cycle of bandwidth is required to provide a 10^{-4} bit error probability. Hence, without diversity, average error probability performance appreciably poorer than 1K 10^{-4} will be obtained.

Figure 5-6 illustrates the improvement in SNR that is attainable with M independently fading diversity copies of the signal using post-detection maximum ratio combining. These curves are simply derived from the expressions*

$$P_M = 1/2 \ (2 \ P_i)^M, \text{ and } P_i = \frac{1}{S/N}$$

*These expressions are strictly applicable only for independent Gaussian noise. Note that in the presence of atmospheric noise, there is statistical dependence between the noise on the different diversity receivers that will tend to reduce the effectiveness of diversity. This reduction has been estimated as less than 1.5 dB for dual diversity and 4.5 dB for quadruple diversity, and has not been reflected in the accompanying figure and table.

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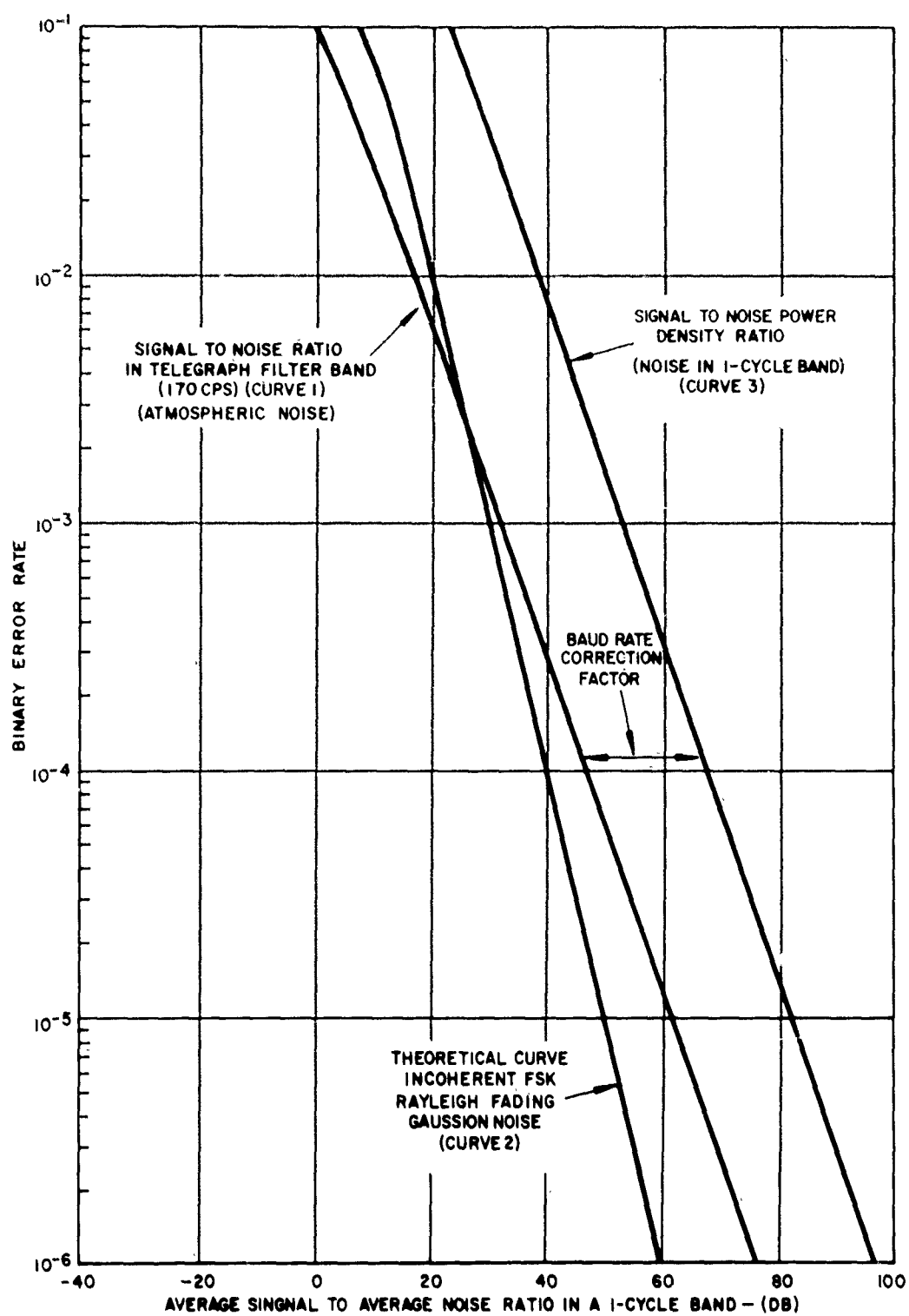
Figure 5-5. Binary Error Rate as a Function of
Signal to Noise

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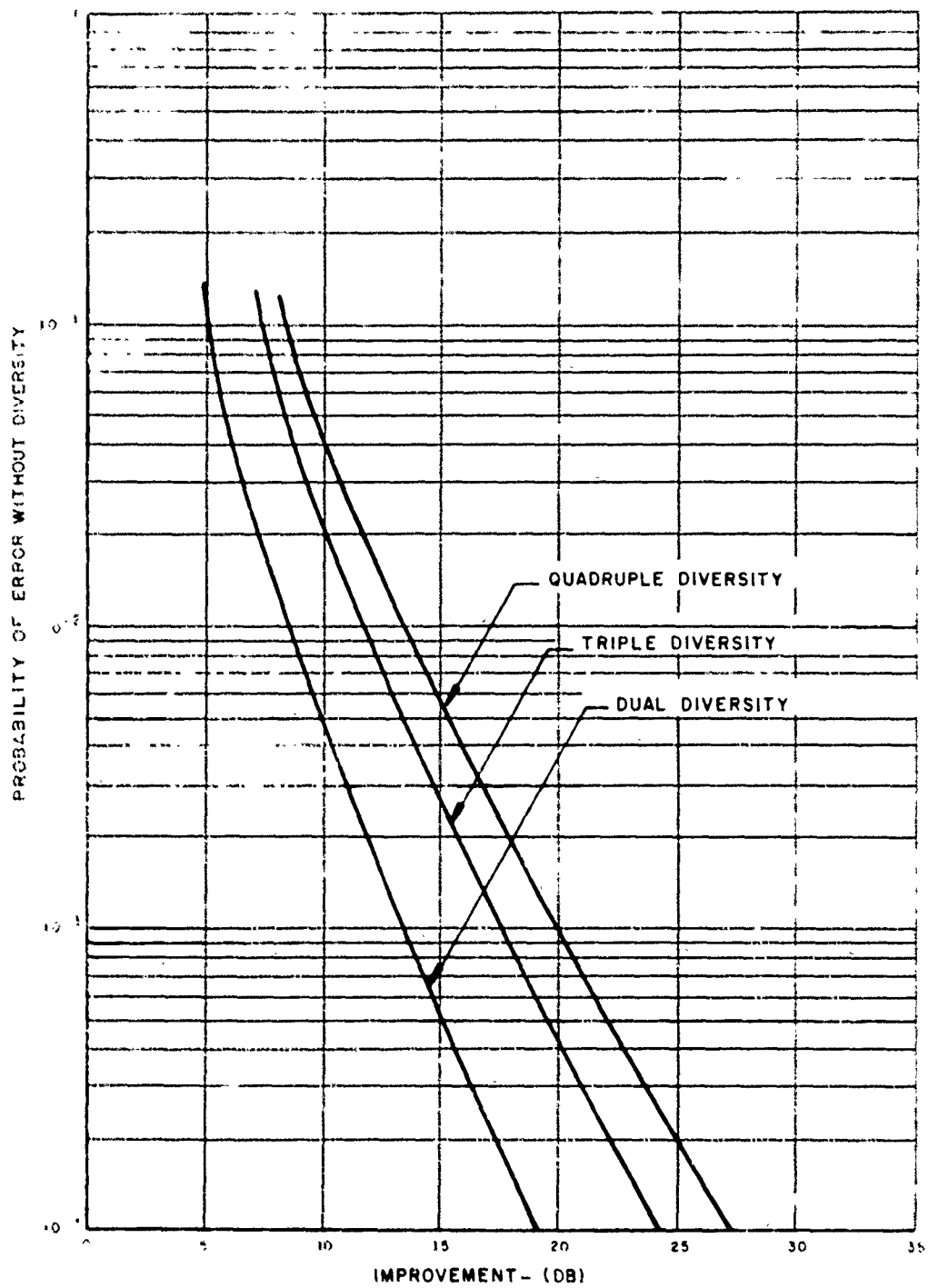
Figure 5-6. Improvement in Signal to Noise
Achieved by Use of Diversity

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where

P_i = bit error probability without diversity

M = order of diversity

P_M = bit error probability with Mth order diversity

The average SNR per cycle of bandwidth required to
achieve a specified error rate can now be specified as a
function of the order of diversity. A tabulation of this
quantity is included in Table 5-3.

TABLE 5-3. AVERAGE SNR PER CYCLE OF BANDWIDTH REQUIRED
TO ACHIEVE SPECIFIED ERROR RATE

| | AVERAGE SIGNAL TO AVERAGE NOISE RATIO (dB) | | | |
ERROR RATE	NO DIVERSITY	DUAL DIVERSITY	TRIPLE DIVERSITY	QUADRUPLE DIVERSITY
1×10^{-6}	97	68	61	55
3×10^{-6}	90	63	57	52
1×10^{-5}	82	58	51	47
1×10^{-4}	67	48	43	40
1×10^{-3}	53	39	35	33

From this table we observe that, with 54 dB SNR per
cycle of bandwidth, the error probability with no diversity
is approximately 10^{-3}, with dual diversity it is 2×10^{-5},
for quadruple diversity it is 10^{-6}. For the tactical envir-
onment, dual diversity operation is most probable.

For the bit rates prevalent in HF systems frequency se-
lective fading effects can contribute substantially to the
total error probability. Table 5-4 has been prepared using
analytical techniques described in the literature[10], to com-
pare the relative contribution of noise and multipath to the
overall error probability. Phase continuous binary FSK modu-
lation with a 13.3-ms band duration was selected for this
calculation. The entry in the upper diagonal part of the
square is the error probability due to multipath. The error
probability due to noise is in the lower diagonal part of
the square. For each channel condition pair, the larger of

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the two error probabilities is identified by shading. It may
be seen from the table that 2.5-ms multipath is the limiting
performance factor for a SNR of 34 dB. With 4.2-ms multipath
the link quality is extremely poor and error probability is
significantly worse than that caused by a SNR of 21 dB. Even
1-ms multipath causes as many errors as a SNR of 48 dB.

    c.   Short Haul HF Performance Calculations

        For the purposes of this calculation we will assume
that the following conditions prevail:

Time:	June 2000 hours
Geography:	Central Germany
Propagation Mode:	1 hop F layer
Frequency:	6 kHz
Sunspot Number:	10
Range:	200 miles

        Assuming identical transmitting and receiving antennas,
the skywave system loss $L_{sw} = L_p - 2G(0,f)$

where

$$L_p = \text{propagation loss} = 114 \text{ dB}[9]$$

$G(0,f)$ = antenna gain (a function of radiation angle
            and frequency)

        For a log-periodic antenna, the antenna Gain $G_{(L)}$ rela-
tive to an isotropic antenna is assumed to be 10 dB.[L)

        The virtual height of the F_1 layer is 150 miles. This
results in a radiation angle 0, for a 200 mile path of 55°.
For a 15-foot vertical whip antenna and the conditions
stated above, the resultant antenna gain $G_{(W)}$ at 6 MHz rela-
tive to an isotropic antenna is -9.5 dB.

        Therefore for log-periodic antennas

$$L_{sw}(L) = 94 \text{ dB}$$

        For a 15 foot vertical ship

$$L_{sw}(W) = 133 \text{ dB}$$

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In the latter case, an analytical expression which closely approximates the skywave loss as a function of operating frequency and distance (for distances between 30 and 600 miles) is

$$L_{sw} = 147 - 16.7 \log f_{MHz} + 25 \left(\log \frac{d_{mi}}{330}\right)^2$$

1. <u>Noise</u>: At 6 MHz, atmospheric noise is the dominant noise source. For the system and environmental parameters assumed above, the noise power level in dB above kTB not exceeded for 50 percent of the hours, is 50 dB. Including the antenna gain characteristic for vertical whip the noise power level input to the receiver, $\overline{N}_{50\%}$ is 40.5 dB above kTB 50 percent of the hours. The corresponding noise power level exceeded 10 percent of hhe hours, $N_{10\%}$, is 52.2 dB above kTB. The corresponding values for the log periodic antenna are $\overline{N}_{50\%} = 60$ dB and $N_{10\%} = 71.7$ dB above kTB.

2. $\overline{SNR}$: To calculate $\overline{SNR}$, where $\overline{S}$ is the average signal power, we need only specify the transmitter power and the receiver bandwidth. The modulation technique and receiver filter characteristic are relevant. Let us assume, however, for the purpose of this calculation, a bit rate of 75 b/s and a receiver bandwidth of 170 Hz. Assume also a transmitter power of 1000 watts.

Then in the case of the vertical whip,

$$\overline{S}/N_{50\%} = 30 - 133 - (-204 + 22.3 + 40.5)$$
$$= 38.2 \text{ dB}$$

and

$$\overline{S}/N_{10\%} = 26.5 \text{ dB}$$

For log periodic antennas

$$\overline{S}/N_{50\%} = 30 - 94 - (-204 + 22.3 + 60)$$
$$= 57.7 \text{ dB}$$

$$\overline{S}/N_{10\%} = 46 \text{ dB}$$

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For the vertical whip,

Assuming no diversity, FSK modulation, matched filter envelope detection, a Rayleigh fading medium and atmospheric noise, the average error probability with noise as the sole disturbance, for 50 percent of the hours is 3×10^{-4}. For 10 percent of the hours it is approximately 2×10^{-3}. This result is obtained by converting the above S/N values to a per cycle of bandwidth basis and comparing the results with the entries in the first column of Table 5-3.

Similarly, for a log periodic antenna, the corresponding error probabilities are 1×10^{-5} and 1×10^{-4}.

The above results, of course, neglect the effects of multipath, which can be very severe in short-haul HF paths. Table 5-4 can be used to determine the contribution of multipath to error probability if the multipath activity on the link is established.

TABLE 5-4.   RELATIVE CONTRIBUTION OF NOISE AND MULTIPATH TO
OVERALL ERROR PROBABILITY

$\frac{1}{B_c}$ T	0.84 ms	2.54 ms	4.22 ms
SNR	.1	.3	.5
21 dB	5.0×10^{-5} / 1.0×10^{-2}	4.5×10^{-3} / 1.0×10^{-2}	1.4×10^{-1} / 1.0×10^{-2}
34 dB	5.0×10^{-5} / 1.0×10^{-3}	4.5×10^{-3} / 1.0×10^{-3}	1.4×10^{-1} / 1.0×10^{-3}
48 dB	5.0×10^{-5} / 1.0×10^{-4}	4.5×10^{-3} / 1.0×10^{-4}	1.4×10^{-1} / 1.0×10^{-4}

LEGEND:

B_c = CORRELATION BANDWIDTH

T = ASSUMED BAUD DEVIATION = 13.3 ms

▽ = ERROR PROBABILITY DUE TO MULTIPATH

△ = ERROR PROBABILITY DUE TO NOISE

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SECTION 6

INTEGRATED SYSTEM EFFECTIVENESS MODEL

The integrated system effectiveness model combines all of the input data into a single explicit value of system effectiveness. This takes into consideration the intrinsic benefit that can be obtained from the performance capability, the operational readiness of the system, the continuity of performance and finally the risk factors if any parts of the system are proposed future developments. The technical basis for this model was established in Section 2, and this section presents a step-by-step explanation of the model together with a sample problem. Appendix D contains the calculations for the sample problem.

6.1 DESCRIPTION OF MODEL

To describe the model, we will solve the sample problem while proceeding through each step of the model operation. The network to be evaluated is shown in Figure 6-1. It includes four signal centers, brigade headquarters (BQ), division main (DM), division alternate (DA) and Army Area Communications (AA). Except for brigade headquarters, the other three have store and forward facilities. The connectivity is given in Table 6-1.

Associated with each signal center are a number of military units. The traffic demand amongst these units has been analyzed from their distributions to determine the busy-hour traffic. For simplicity we are assuming the same amount of traffic flows in each direction between two units. The traffic demand is given in the Traffic matrix of Table 6-2. Only two priority levels are specified, to minimize the computations.

To illustrate the reading of Table 6-2, the traffic from DA to DM during the busy hour is: 10 call minutes of voice priority 1; 18 call minutes of voice priority 2; 8 TTY messages priority 1; 32 TTY messages priority 2; 100 data messages priority 1; and 400 data messages priority 2. The average holding time of voice calls is 2 minutes; average length of TTY messages is 200 groups; and data messages are transmitted at 2400 bits per second, average duration 2 seconds. The allowed delay or perishability is 15 minutes for priority 1 and one hour for priority 2. This perishability time must include preparation and delivery time for TTY and Data messages.

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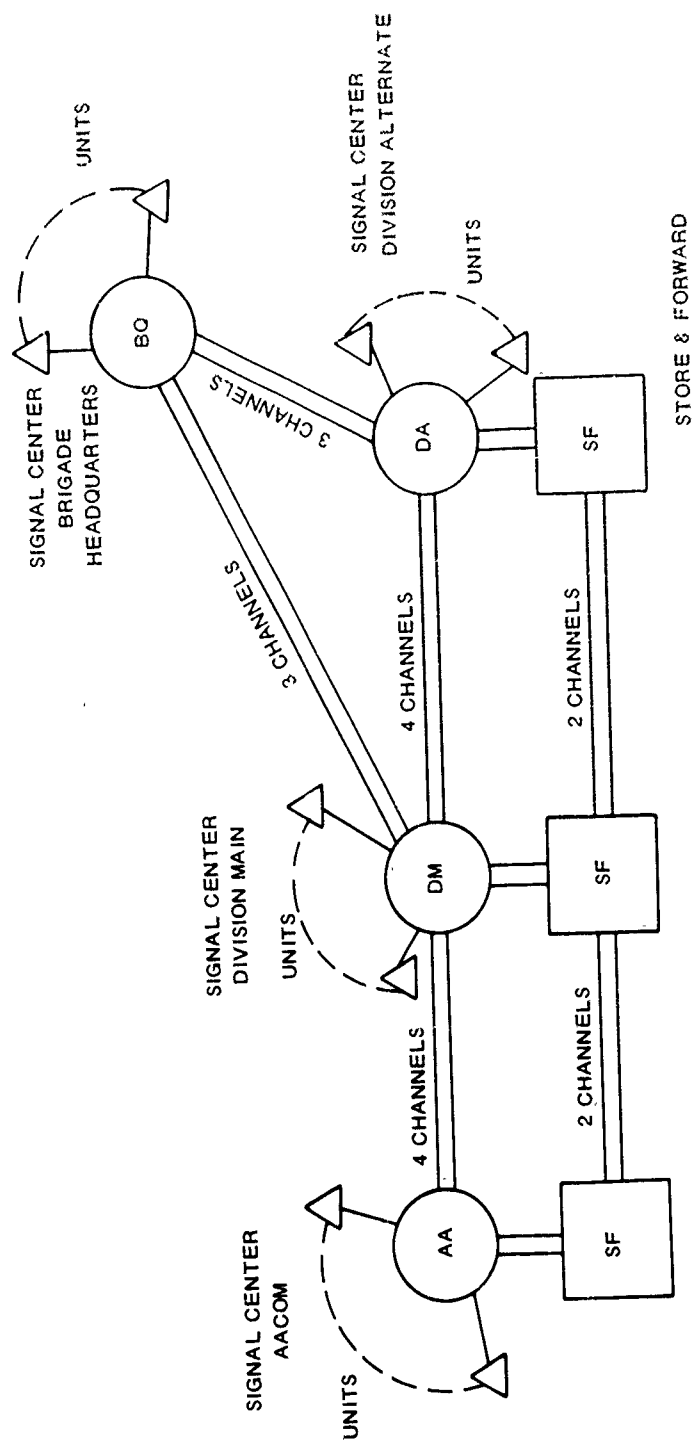
Figure 6-1. Network Configuration of Sample Problem

TABLE 6-1.   CONNECTIVITY - SAMPLE PROBLEM - NUMBER CHANNELS

SIGNAL CENTER	BQ	DA	DM AA
BQ	/////		
DA	3 CS	/////	
DM	3 CS	4 CS 2 SF	/////
AA	0	0	4 CS 2 SF

LEGEND:
CS: Circuit switched
SF: Dedicated store and forward

The routing matrix for this problem is shown in Table 6-3. To illustrate the reading of this matrix, consider the routes from BQ to AA. The first leg of the primary route (1) is to DM for both voice and TTY/Data. We then look up the route from DM to AA which is the second leg shown as the link to AA for voice and the link AASF for TTY/Data. For the secondary route (2) the first leg is to DA and we look up DA to AA which shows the second leg is the DM link for voice and DMSF link for TTY/Data. The third leg is, of course, the same as for the primary route.

6.2 SUMMARY OF STEPS IN MODEL'S OPERATION

We have now completed a description of the first three steps of the model's operation. A summary of all ten steps follows:

a.   Step 1 - Draw the network configuration and connectivity matrix for the system to be evaluated. This may be done to any level of detail desired. A signal center, for example, may be expanded to show a subnetwork of service facilities. The appropriate level of detail is determined by the nature of the problem being solved.

b.   Step 2 - Compile the traffic matrix for the requirements of the busy period. This matrix will show the total traffic from source to destination by type, voice, TTY, or data, and by priority, 1,2,3, et cetera. Voice traffic will usually be in total calls and average holding time.

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TABLE 6-2. TRAFFIC MATRIX – SAMPLE PROBLEM

SIGNAL CENTER	PRIORITY	BQ 1	2	3...	DA 1	2	3...	DM 1	2	3...	AA 1	2	3...
BQ	VOICE	▩			1	6		8	24		0	4	
	TTY	▩			6	20		12	40		8	20	
	DATA	▩			0	0		100	400		0	0	
DA	VOICE	1	6		▩			10	18		3	14	
	TTY	6	20		▩			8	32		5	30	
	DATA	0	0		▩			100	400		100	600	
DM	VOICE	8	24		10	18		▩			14	36	
	TTY	12	40		8	32		▩			10	60	
	DATA	100	400		100	400		▩			100	600	
AA	VOICE	0	4		3	14		14	36		▩		
	TTY	8	20		5	30		10	60		▩		
	DATA	0	0		100	600		100	600		▩		

Voice is in call minutes, avg. holding time 2 minutes
TTY is in messages, avg. length 200 groups, 100 wpm
Data is in messages 2400 b/s, avg. length 2 seconds
Perishability Priority 1: 15 minutes 2: 1 hour

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TABLE 6-3. ROUTING MATRIX – SAMPLE PROBLEM

SIGNAL CENTER	PRIMARY ALTERNATE	BQ VOICE	BQ TTY DATA	DA VOICE	DA TTY DATA	DM VOICE	DM TTY DATA	AA VOICE	AA TTY DATA
BQ	1	▨	▨	DA	DA	DM	DM	DM	DM
	2	▨	▨	DM	DM	DA	DA	DA	DA
DA	1	BQ	BQ	▨	▨	DM	DMSF	DM	DMSF
	2	DM	DMSF	▨	▨	–	–	–	–
DM	1	BQ	BQ	DA	DASF	▨	▨	AA	AASF
	2	DA	DASF	–	–	▨	▨	–	–
AA	1	DM	DMSF	DM	DMSF	DM	DMSF	▨	▨
	2	–	–	–	–	–	–	▨	▨

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TTY traffic will usually be expressed as total messages and average number of groups, and data traffic as number of messages, transmission rate (BPS) and average duration in seconds.

c. Step 3 - Develop the routing matrix for the configuration from each source to each destination by circuit type and for all allowable routes. Circuit types will usually be shown as voice or circuit switched, or store and forward circuits for TTY and data. Of course data may also be carried on circuit switched links. The matrix is constructed to show all allowable routes: primary, secondary, tertiary, and so forth.

We now proceed with the rationale for steps 4, 5, and 6. As a token representation to incorporate the criteria of size, weight, mobility and transportability, we will specify that the signal center at brigade headquarters (BQ) moves an average of once per day, and takes an average of two hours for tear-down, transport, and set-up time. Thus, there is a probability of interruption of service during the busy period on links BQ-DA and BQ-DM. To account for this, we introduce highest priority (0) traffic which is fictitious in nature and which seizes those links for the probability of down time. This is computed as follows:

$$A_O = \frac{\alpha}{\beta} C$$

where:

$$\alpha = \text{arrival rate} = \frac{1}{24}$$

$$\frac{1}{\beta} = \text{duration} \quad = 2$$

$$C = \text{channels} \quad = 3$$

therefore:

$$A_O = 0.25$$

Down-time traffic $= 0.25 \times 60 = 15$ channel minutes per hour

In a similar manner, we incorporate the criteria of availability, reliability, and maintainability. Let us specify that each of the channels has a MTBF of 250 hours, and a MTTR of 2 hours. Then the outage traffic per channel can be expressed as

$$A_O = \frac{\alpha}{\beta} = 8 \times 10^{-3}$$

where:

$$\alpha = \frac{1}{250} = 4 \cdot 10^{-3}$$

$$\frac{1}{\beta} = 2$$

Down-time traffic = $8 \cdot 60 \cdot 10^{-3}$ = 0.48 minutes per channel per hour

With respect to quality of service, we will assume a reduction in signal-to-noise ratio requiring 5 percent of the data traffic to be repeated on the BQ-DA and BQ-DM links. We now summarize these three steps as follows:

d. Step 4 - Operational readiness is determined by moves from one location to another if the equipment is not in operation during the move. Determine the frequency of moves and the environment from the scenario. Calculate the down time from mobility and transportability calculations. This span covers tear-down, transport, and set-up time. Then the down time is incorporated into the model by fictitious down-time traffic which has zero priority: that is, highest order, and seizes the facilities for the down time. The amount of such traffic per channel is the frequency of moves times the duration.

e. Step 5 - Continuity of performance is determined by such criteria as availability, reliability, maintainability, and survivability. For incorporation into the model we determine for each facility a composite MTBF and a composite MTTR. Then in a manner similar to Step 4, we generate down-time traffic in which the frequency or arrival rate is the MTBF and the duration is the MTTR.

f. Step 6 - The determination of intrinsic benefit is partly influenced by the quality of service and vulnerability. This is incorporated into the model by adding a percent of redundant traffic to each link or facility in

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proportion to that traffic which had to be repeated. Redundant traffic, however, is not counted in the summation for intrinsic benefit.

In the sample problem we will incorporate the risk factor by specifying that the 2400 b/s data modems planned for the time frame of interest have an 80 percent probability of being operational. In the event they are not operational, older units will be used which operate at 1200 b/s.

g. Step 7 - Identify the components of the system that have a future risk factor. Specify the probability of realizing the development and manufacture by the time frame of interest. Also specify what fall-back measures will be taken in the event that the high-risk items are not realized.

In a sense, the first seven steps represent the preparation of input data to the model. We now proceed to the operational steps. A simplified traffic summary is shown in Table 6-4. Based on the previous steps we calculate redundancy (R) traffic and down-time (D) traffic, and prepare a compilation by nodes in the network and by priority. Each compilation will be:

	0&1	2
R		
D		▨
T/D		
V		

TABLE 6-4. TRAFFIC SUMMARY

		DA		DM		AA	
		1	2	1	2	1	2
BQ	V	2	12	16	48	0	8
	T	12	40	24	80	16	40
	D	0	0	200	800	0	0
DA	V			20	36	6	28
	T			16	64	10	60
	D			200	800	200	1200
DM	V					28	72
	T					20	120
	D					200	1200

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The result for the sample problem is shown in Figure 6-2.

    h. Step 8 - Prepare the network traffic summary by showing the following tabulation for each node pair:

        1. Redundant traffic R by priority

        2. Down-time traffic D (0) priority only

        3. Teletype and data T/D by priority

        4. Voice traffic V by priority

If the system configuration multiplexes 16 TTY circuits on one channel, the TTY traffic should be separated from the data.

    i. Step 9 - Determine the traffic distribution by priority, starting with 0 and 1, and adding one additional priority category for each computation. Thus, the computations of traffic distribution will take on the following patterns:

COMPUTATION NUMBER	PRIORITIES INCLUDED
1	0, 1
2	0, 1, 2
3	0, 1, 2, 3
.	.
.	.
.	.
n	0, 1, 2, 3, ... n

    This distribution is determined using the Erlang C probability formula in which all traffic waits indefinitely for service. The formula is:

$$C(c,a) = \frac{\dfrac{c}{c-a}}{\dfrac{c}{c-a} + \left(\dfrac{a^c}{c!}\right)^{-1} \displaystyle\sum_{o}^{c-1} \dfrac{a^x}{x!}}$$

    We recognize that this type of problem requires an iterative solution, because we need to know the answer in order to solve for it. We start by assuming a $C(c,a)$ value
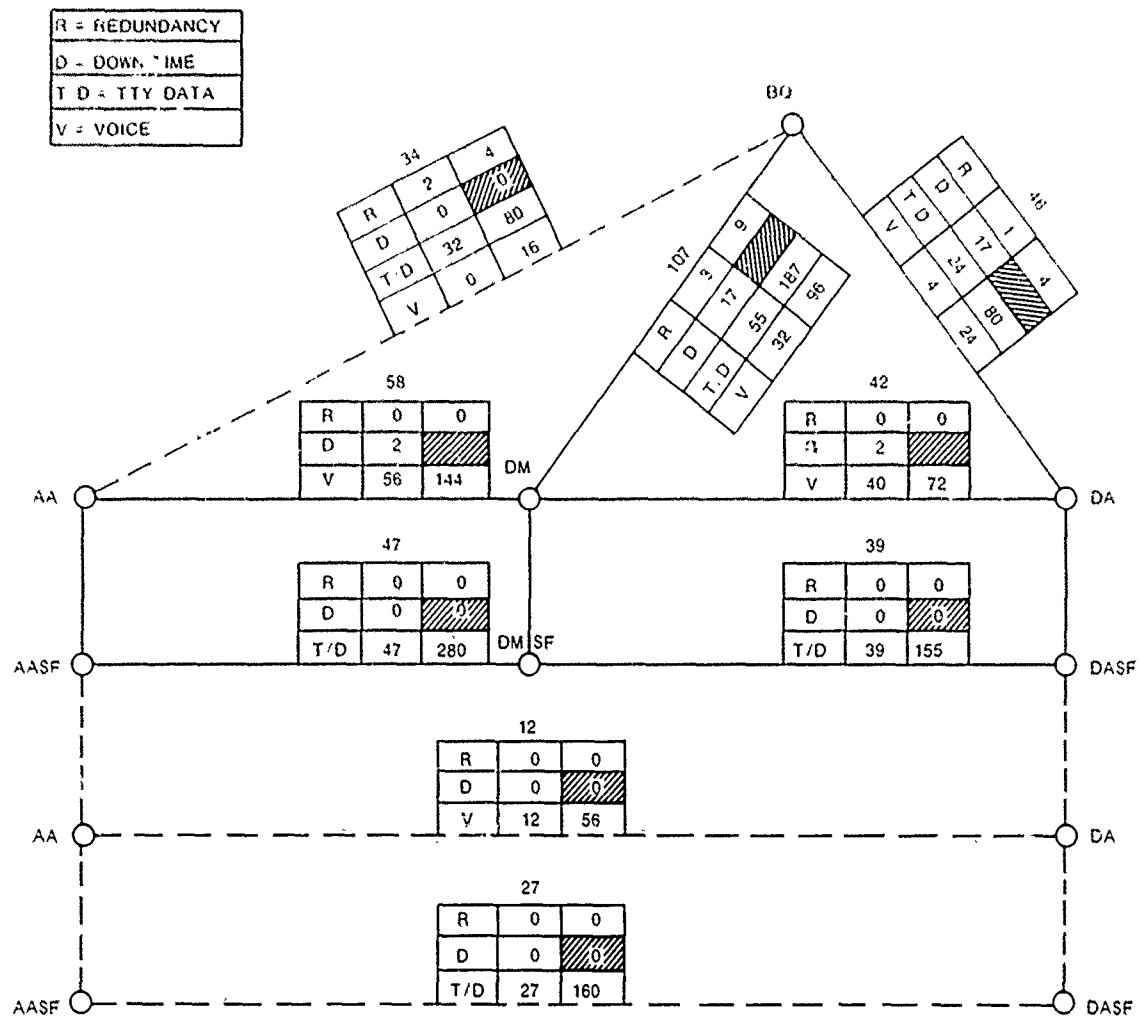
Figure 6-2.   Network Traffic Summary

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of 0.1 for each link, and distribute all traffic by node pair; then calculate the new C(c,a) value and repeat until convergence is obtained (usually 7 iterations).

Appendix D contains the computations for 5 iterations of the sample problem for priority 0 and 1 traffic distribution. This data includes five link-loading tables, four algorithm tables, and four Erlang C calculations. The values obtained after 5 iterations were considered close enough for the sample problem.

Since the perishability or priority 1 was specified as 15 minutes, we will assume a preparation time of five minutes for all traffic: voice, teletype and data. This tends to favor the data traffic, since voice usually requires less preparation time. In detailed operation of the model, separate priority categories should be assigned to voice and data even if they have the same total perishability time. Now we wish to calculate the probability of delay exceeding 10 minutes for priority 0 and 1 traffic. Circuit-switched traffic is computed end-to-end, while store-and-forward traffic is computed for each link en route.

The computations for the probability of delay are presented in Appendix D. Since this sample problem is being solved by manual calculations, we selected certain arbitrary values of a, b, and c, which correspond to the sample problem. The results have been plotted on a graph in Appendix D to facilitate extrapolation to in-between values. The actual calculated points are:

Set 1	a = 1 Erlang	Set 4	a = 1.5 Erlang
	c = 2 channels		c = 2 channels
delay (d) = 3, 6, 10		d = 3, 6, 10
	minutes		minutes
Set 2	a = 1 Erlang	Set 5	a = 2 Erlang
	c = 3 channels		c = 3 channels
	d = 3, 6, 10		d = 3, 6, 10
	minutes		minutes
Set 3	a = 1 Erlang		
	c = 4 channels		
	d = 10 (only)		
	minutes		

Summary calculations for the priority 1 voice traffic
is presented in Table 6-5, and for data and teletype traffic
in Table 6-6. The probabilities extrapolated from the graph
in Appendix D are shown on the appropriate link in Figure
6-3. For the first set of computations covering priority 0
and 1, the following results were obtained:

	TRAFFIC OFFERED	DELAYED* > 15 minutes
VOICE	144	0.178
DATA AND TTY	224	10.36

*10 minutes plus 5 minutes preparation

The calculations for computation series number 2 would
include the total traffic for priority 0 plus 1 plus 2. The
procedure for calculating the amount of offered traffic
delayed more than one hour would be exactly the same as the
procedure illustrated thus far. Since this would not add
anything new to the procedure, we will terminate the numer-
ical calculations at this point.

TABLE 6-5. SUMMARY CALCULATIONS, VOICE TRAFFIC (PRIORITY 1)

NODE PAIR	VOICE TRAFFIC CALL MINUTES	DELAY < 10 MIN		DELAYED > 10 MIN.
		CARRIED	ALTERNATE ROUTE	
BQ--DA	4	3.95 0.048	0.05	0.002
BQ-DM	32	30.66 1.223	1.34	0.017
DA-DM	40	39.94		0.06
DA-AA	12	11.996		0.004
DM-AA	56	55.905		0.095
TOTAL	144			0.178

In priority 1 voice traffic, of 144 call minutes offered
traffic, 0.178 call minutes were delayed more than 10
minutes.

TABLE 6-6. SUMMARY CALCULATIONS, TELETYPE AND DATA TRAFFIC (PRIORITY 1)

NODE PAIR	DATA TRAFFIC EQUIVALENT CALL-MINUTES	NUMBER OF LINKS	DELAY < 10 Min CARRIED ON LINKS	ALTERNATE ROUTE	DELAYED > 10 Min
BQ-DA	24	1 2	23.688 0.3	0.312	0.012 (est)
BQ-DM	55	1 2	52.69 2.0	2.31	0.30
DA-DM	39	1	36.58	2.418	
DA-AA	27	2	21.63		5.37
DM-AA	47	1	43.0		4.00
BQ-AA	32	2 3	26.32 5.0	5.68	0.68 (est)
TOTAL	224				10.36

Allowed Delay Values

DA-AA Delay divided 5.8 and 4.2
BQ-AA Primary divided 3.3 and 6.7
BQ-DM Secondary divided 1.7 and 8.3

In priority 1 data and teletype traffic of 224 equivalent call minutes offered traffic, 10.36 call minutes were delayed more than 10 minutes.

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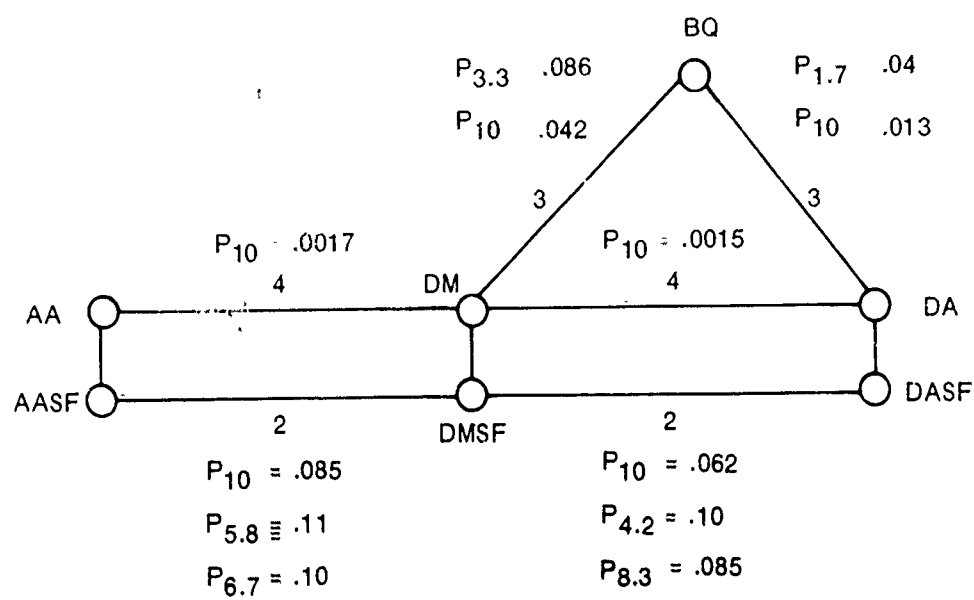
Figure 6-3. Probability of Delay Used in
Computations Extrapolated from Graph
in Appendix D

To incorporate the risk factor, we would have to compute again for 1200 b/s in place of 2400 b/s. Then, having the measure of benefit for each, we combine the two as follows:

$.8$ probability of 2400 b/s
$.2$ probability of 1200 b/s

$$\text{Benefit } B = 0.8\ B_{2400} + 0.2\ B_{1200}$$

j. Step 10 - Compute the system benefit by calculating the information transferred within the allowed time times the required speed of transfer. This is summed for each priority class. Note that down-time traffic and redundant traffic are not considered when computing the benefit. System effectiveness is then expressed as the ratio of benefit to requirement if we can assume that the specified traffic is the requirement.

To calculate benefit (B) we proceed as follows (assuming only the results of priority 1 traffic):

Voice: 144 call minutes (essentially not delayed)
$$(144)\ (60)\ (25) = 216{,}000 \text{ bits}$$
$$\left(\frac{\text{sec}}{\text{min}}\right)\left(\frac{\text{bits}}{\text{sec}}\right)$$

Teletype: 196 call minutes 4.63% delayed
$$(196)\ (95.37)\ (60)\ (8) = 8{,}971{,}200 \text{ bits}$$
$$(\%)\quad \left(\frac{\text{sec}}{\text{min}}\right)\left(\frac{\text{bits}}{\text{sec}}\right)$$

Data: 28 call minutes 4.63% delayed
$$(28)\ (95.37)\ (60)\ (1920) = 307{,}584{,}000 \text{ bits}$$
$$(\%)\quad \left(\frac{\text{sec}}{\text{min}}\right)\left(\frac{\text{bits}}{\text{sec}}\right)$$

Summary:

Voice	216,000	bits
Teletype	8,971,000	bits
Data	307,584,000	bits
Total	316,771,000	bits

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Allowed delay was 15 minutes or 900 seconds, therefore:

Benefit = $\dfrac{316,771,000}{900}$ = 352,000 shannon information bits per allowed delay second.

6.3 APPLICATION OF MODEL TO MORE REALISTIC PROBLEM

The somewhat unbalanced result between voice and data in this sample problem comes about because we assigned the same 5-minutes preparation time to each. In a more realistic problem the preparation time for voice is negligible, while that for data will usually run more than 5 minutes. This would produce a more reasonable balance in the measure of benefit.

Table 6-7 calculates system effectiveness for priority 1 traffic only.

TABLE 6-7. SYSTEM EFFECTIVENESS (PRIORITY 1)

	REQUIRED	DELIVERED (within time allowed)	SYSTEM EFFECTIVENESS (%)
DATA	322,560,000	307,584,000	95.36
TTY	9,408,000	8,971,000	95.36
VOICE	216,000	216,000	100
TOTAL	332,184,000	316,771,000	Avg. 95.36

Integrated Systems Effectiveness = 95.36% (priority 1 traffic only)

SECTION 7

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APPENDIX A

DERIVATION OF PROBABILITY EQUATION USED IN THE MODEL

For the sake of brevity, we will refer to all messages or data as calls. Now we define three constants, α, β, and γ, to be the average values of the traffic parameters, as follows:

α : New call arrival rate

α^{-1}: time between new calls

β : termination rate calls in progress

β^{-1}: duration of calls in progress

γ : expiration rate delays exceeding perishability

γ^{-1}: perishability time

We can now write the exponential expressions for the probability of each event taking t minutes or longer:

time between calls (t´) $\quad P(t´ \geq t) = \varepsilon^{-\alpha t}$ $\qquad$ (A-1)

holding time (h) $\qquad P(h \geq t) = \varepsilon^{-\beta t}$ $\qquad$ (A-2)

expiration time (d) $\qquad P(d \geq t) = \varepsilon^{-\gamma t}$ $\qquad$ (A-3)

We can do the same for the probability that each event may occur in a given time differential dt:

new call $\qquad P(\alpha) = \alpha \ dt$ $\qquad$ (A-4)

terminated call $\quad P(\beta) = \beta \ dt$ $\qquad$ (A-5)

expired delay $\qquad P(\gamma) = \gamma \ dt$ $\qquad$ (A-6)

We will also assume that, if the delay in queue exceeds the perishability time of the call, it will leave the system. This says there are two ways for a new call (α) to leave the system: a normally completed or terminated call (β) and a call that is cancelled out because the allowable delay has expired (γ). In the real system, this is usually the case for voice communication, but not for data or store-and-

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forward traffic. It will therefore be necessary to adjust for this difference in the operation of the model.

Referring back to Figure 2-2, we define all possible states of the parallel facilities as the probability, p_i, that facility i is busy. Since we have assumed a condition of statistical equilibrium, it is equally probable that we will change to state p_{i+1} or p_{i-1}. As we said before, at any instant of time, the probability of a new call arriving is the same as the probability of a call leaving. Note also that we are dealing with conditional probabilities that require the product of two factors. If we are in state p_i, the probability of going to state p_{i+1} is

$$p(i+1) = \alpha dt \; p_i \qquad\qquad (A-7)$$

Conversely, if we are in state p_i+1, the probability of going back to p_i is

$$p_i = p(i+1-1) = (i+1)\beta dt \; p_{(i+1)} \qquad\qquad (A-8)$$

Since these state changes are equally probable

$$\alpha dt \; p_i = (i+1)\beta dt \; p_{(i+1)} \qquad\qquad (A-9)$$

Thus with Equation A-9, we can write the complete set of state change equations as follows:

$$\alpha dt \; p_o = \beta dt \; p_1$$

$$\alpha dt \; p_1 = 2 \; \beta dt \; p_2$$

$$\alpha dt \; p_2 = 3 \; \beta dt \; p_3$$

$$\vdots$$

$$\alpha dt \; p_i = (i+1)\beta dt \; p_{(i+1)}$$

$$\vdots$$

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for c parallel facilities in group A (Figure 2-2)

$$\alpha dt \; p_{c-1} = c\beta dt \; p_c \qquad\qquad (A-10)$$

Now the use of the storage facilities in group B (Figure 2-2)

$$\alpha dt \; p_c = (c\beta+\gamma)dt \; p_{c+1}$$

$$\alpha dt \; p_{c+1} = (c\beta+2\gamma)dt \; p_{c+2}$$

$$\alpha dt \; p_{c+2} = (c\beta+3\gamma)dt \; p_{c+3}$$

$$\vdots$$

$$\alpha dt \; p_{c+y-1} = (c\beta+y\gamma) \; dt \; p_{c+y}$$

Since α, β, and γ are constants independent of time, we integrate both sides of each equation over the busy period, T, and divide by T to eliminate time from the equations. By substituting the first equation in the second, the second in the third, and so forth, we can express all values of p_i as a function of p_o:

$$P_o = P_o$$

$$P_1 = P_o \frac{\alpha}{\beta}$$

$$P_2 = P_o \left(\frac{\alpha}{\beta}\right)^2 \frac{1}{2\cdot 1}$$

$$P_3 = P_o \left(\frac{\alpha}{\beta}\right)^3 \frac{1}{3\cdot 2\cdot 1}$$

$$\vdots$$

$$P_i = P_o \left(\frac{\alpha}{\beta}\right)^i \frac{1}{i!}$$

$$\vdots$$

$$P_c = P_o \left(\frac{\alpha}{\beta}\right)^c \frac{1}{c!}$$

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$$P_{c+1} = P_o \ \left(\tfrac{\alpha}{\beta}\right)^c \ \frac{1}{c!} \cdot \frac{\alpha}{(c\beta+\gamma)}$$

$$P_{c+2} = P_o \ \left(\tfrac{\alpha}{\beta}\right)^c \ \frac{1}{c!} \cdot \frac{\alpha^2}{(c\beta+\gamma) \ (c\beta+2\gamma)}$$

$$\vdots$$

$$P_{c+y} = P_o \ \left(\tfrac{\alpha}{\beta}\right)^c \ \frac{1}{c!} \cdot \frac{\alpha^y}{(c\beta+\gamma) \ (c\beta+2\gamma) \ \ldots \ (c\beta+y\gamma)} \quad \text{(A-12)}$$

We can simplify these equations by introducing two new terms:

   a.   The traffic load, on the system can be expressed as the product of calling rate α and the duration of each call, $1/\beta$:

$$a = \frac{\alpha}{\beta}$$

   b.   The delay tolerance, b of the system can be expressed as the ratio of the duration of each call, $1/\beta$, to the perishability time, $1/\gamma$:

$$b = \frac{\gamma}{\beta}$$

Then, the general term of equation (A+12) becomes:

$$P_{c+y} = P_o \cdot \frac{a^c}{c!} \cdot \frac{a^y}{(c+b) \ (c+2b) \ \ldots \ (c+yb)} \quad \text{(A-13)}$$

Also, using the product notation Π

$$\prod_{j=1}^{y} (c+jb) = (c+b) \ (c+2b) \ \ldots \ (c+yb)$$

The set of probability equations becomes

$$p_0 = p_0$$

$$p_1 = p_0 \cdot a$$

$$p_2 = p_0 \cdot \frac{a^2}{2!}$$

$$p_3 = p_0 \cdot \frac{a^3}{3!}$$

$$\vdots$$

$$p_c = p_0 \cdot \frac{a^c}{c!}$$

$$p_{c+1} = p_0 \cdot \frac{a^c}{c!} \cdot \frac{a}{(c+b)}$$

$$p_{c+2} = p_0 \cdot \frac{a^c}{c!} \cdot \frac{a^2}{(c+b)\ (c+2b)}$$

$$\vdots$$

$$p_{c+y} = p_0 \cdot \frac{a^c}{c!} \cdot \frac{a^y}{\prod\limits_{j=1}^{y} (c+jb)} \qquad (A-14)$$

Provided all calls that enter the system also leave it, and provided there are more storage facilities than possible calls, we can say that we have a conservative system that at any instant occupies one and only one state, and further that every such state has been identified. We are therefore justified in saying that the sum of the probabilities of being in each state covers all possibilities and is therefore a certainty (probability = 1). Hence,

$$\sum_{i=0}^{c+y} P_i = 1 \qquad (A-15)$$

Thus, from equations A-14 and A-15

$$P_0 \left[1 + a + \frac{a^2}{2!} + \ldots \frac{a^c}{c!} + \frac{a^c}{c!} \cdot \frac{a}{(c+b)} + \ldots \frac{a^c}{c!} \ \frac{a^y}{\prod\limits_{j=1}^{y}(c+jb)} \right] = 1 \quad (A-16)$$

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$$(P_o)^{-1} = \sum_{x=o}^{c} \frac{a^x}{x!} + \frac{a^c}{c!} \sum_{y=1}^{Y} \frac{a^y}{\prod\limits_{j=1}^{Y}(c+jb)} \qquad (A-17)$$

We now have the solution for the probability of any state

$$P_{c+y} = \frac{f(y)}{(\frac{a^c}{c!})^{-1} \sum\limits_{x=o}^{c} \frac{a^x}{x!} + \sum\limits_{y=1}^{y} f(y)}$$

where $(A-18)$

$$f(y) = \frac{a^y}{\prod\limits_{j=1}^{Y}(c+jb)}$$

We next wish to determine the probability of calls being delayed beyond their perishability time, that is, when the delay, δ is equal to, or greater than the perishability, γ^{-1}

$$P(\delta \geq \gamma^{-1})$$

The probability of the allowable delay being exceeded is again a conditional probability expressed as the product of two probabilities: (1) of being in a state of delay, (equation A-18) and (2) the probability of expired delay (equation A-6). Hence,

$$P(\delta \geq \gamma^{-1})_{c+y} = P_{c+y} \cdot y\gamma \, dt \qquad (A-19)$$

Then the total number of calls that will probably expire during the busy period is determined by integrating over the time interval and summing for all applicable states as follows:

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$$\sum P(\gamma) = \sum_1^y p_{c+y} \cdot \int_0^T y\gamma \, dt \qquad (A-20)$$

$$= \gamma T \sum_1^y y \, p_{c+y} \qquad (A-21)$$

Now to determine the solution we are looking for, we divide by the total number of calls, n, using the facilities during the busy period. Using equation A-4

$$n = \int_0^T \alpha \, dt = \alpha T \qquad (A-22)$$

Thus from equations A-21 and A-22 the probability of delay exceeding the perishability is

$$P(\delta \geq \gamma^{-1}) = \frac{\sum P(\gamma)}{n} = \frac{\gamma}{\alpha} \sum_1^y y \, p_{c+y}$$

We note that $\frac{\gamma}{\alpha}$ is the ratio of the expiration rate to the new call rate, which can also be expressed as the ratio of the delay tolerance to the traffic load. That is,

$$\frac{\gamma}{\alpha} = \frac{b}{a}$$

The solution in final form is

$$P(\delta \geq \gamma^{-1}) = \frac{\dfrac{b}{a} \sum_1^y y f(y)}{(\dfrac{a^c}{c!})^{-1} \sum_0^c \dfrac{a^x}{x!} + \sum_1^y f(y)} \qquad (A-24)$$

where

$$f(y) = \frac{a^y}{\prod_1^y (c+j b)}$$

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Although equation 2-35 appears complex, the algorithm for its solution to provide numerical values is straight-forward. The algorithm is presented in Tables A-1 and A-2. Let us illustrate their use with an example:

Given:

α = 2 calls per minute

B^{-1} = 1 minute holding time

γ^{-1} = 10 minutes allowed delay

c = 4 parallel facilities plus necessary storage

Solution:

$$a = \frac{\alpha}{B} = 2$$

$$b = \frac{\gamma}{B} = 0.1$$

$$\frac{b}{a} = \quad 0.05$$

Entering the values for a and c in Table A-2, we get

K	L	M	N
0	1	1	1
1	2	2	3
2	1	2	5
3	0.67	1.33	6.33
4	0.50	0.67	7.0

Entering the values for a, b, and c in Table A-2 we get

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ALGORITHM TABLE A-1 FACILITIES

Column	K	L	M	N
Function	$K_i = x$	$L_i = \dfrac{a}{K_i}$	$M_i = L_i\,(M_{i-1})$	$N_i = \sum M_i$
Initial Value	0	1	1	1
Facility Number	1	a	a	$1 + a$
	2	$\dfrac{a}{2}$	$\dfrac{a^2}{2}$	$1 + a + \dfrac{a^2}{2}$
	3	$\dfrac{a}{3}$	$\dfrac{a^3}{3 \cdot 2}$	$1 + a + \dfrac{a^2}{2} + \dfrac{a^3}{3 \cdot 2}$
	$\vdots$ $c-1$	$\dfrac{a}{c-1}$	$\dfrac{a^{c-1}}{(c-1)!}$	$\displaystyle\sum_{x=0}^{c-1} \dfrac{a^x}{x!}$
TOTAL FACILITIES	c	$\dfrac{a}{c}$	$\dfrac{a^c}{c!}$	$\displaystyle\sum_{x=0}^{c} \dfrac{a^x}{x!}$

ALGORITHM TABLE A-2 STORAGE OR WAITING

Column	Q	R	S	T	U	V
Function	$Q_i = (y)$	$R_i = c + Q_i b$	$S_i = \frac{a}{R_i}$	$T_i = \prod S_i$	$U_i = \sum T_i$	$V_i = \sum Q_i T_i$
Storage Number	1	$c + b$	$\frac{a}{c+b}$	$\frac{a}{c+b}$	$\frac{a}{c+b}$	$\frac{a}{c+b}$
Storage Number	2	$c + 2b$	$\frac{a}{c+2b}$	$\frac{a}{c+b}\cdot\frac{a}{c+2b}$	$\left(\frac{a}{c+b}\right)+\left(\frac{a}{c+b}\cdot\frac{a}{c+2b}\right)$	$\left(\frac{a}{c+b}\right)+2\left(\frac{a}{c+b}\cdot\frac{a}{c+2b}\right)$
Storage Number	3	$c + 3b$	$\frac{a}{c+3b}$	$\frac{a}{c+b}\cdot\frac{a}{c+2b}\cdot\frac{a}{c+3b}$	$\left(\frac{a}{c+b}\right)+\left(\frac{a}{c+b}\cdot\frac{a}{c+2b}\right)+\left(\frac{a}{c+b}\cdot\frac{a}{c+2b}\cdot\frac{a}{c+3b}\right)$	$\left(\frac{a}{c+b}\right)+2\left(\frac{a}{c+b}\cdot\frac{a}{c+2b}\right)+3\left(\frac{a}{c+b}\cdot\frac{a}{c+2b}\cdot\frac{a}{c+3b}\right)$
Storage Number	$\ldots\ y$	$c + yb$	$\frac{a}{c+yb}$	$\frac{a^y}{\prod_{j=1}^{y}(c+jb)} = f(y)$	$\sum_{y=1}^{y}\frac{a^y}{\prod_{j=1}^{y}(c+jb)} = \sum_{y=1}^{y}f(y)$	$\sum_{y=1}^{y}\frac{ya^y}{\prod_{j=1}^{y}(c+jb)} = \sum_{y=1}^{y}yf(y)$
Storage Number	$\ldots\ \infty$				$\sum_{y=1}^{\infty}\frac{a^y}{\prod_{j=1}^{y}(c+jb)} = \sum_{y=1}^{\infty}f(y)$	$\sum_{y=1}^{\infty}\frac{ya^y}{\prod_{j=1}^{y}(c+jb)} = \sum_{y=1}^{\infty}yf(y)$
					Discontinue series when change ≤ 0.001	

Q	R	S	T	U	V
1	4.1	.4878	.4878	.4878	.4878
2	4.2	.4762	.2323	.7201	.9524
3	4.3	.4651	.1080	.8281	1.2764
4	4.4	.4545	.0491	.8772	1.4728
5	4.5	.4444	.0217	.8989	1.5813
6	4.6	.4348	.0094	.9083	1.6377
7	4.7	.4255	.0040	.9123	1.6657
8	4.8	.4166	.0017	.9140	1.6793
9	4.9	.4082	.0007	.9147	1.6856
10	5.0	.4000	.0003	.9150	1.6886
11	5.1	.3922	.0001	.9151	1.6898

Then the probability of delay equal to or exceeding 10 minutes is .

$$P(\delta \geq 10m) = \frac{(.05)\ (1.6898)}{\frac{7.0 + .9151}{0.67}}$$

$$= .0074$$

Therefore, in this example it is probable that seven calls out of one thousand will be delayed ten minutes or longer.

TACTICAL FUNCTION: REQUEST FOR HELICOPTER CASUALTY EVACU-
                     ATION

NUMBER: 14

NARRATIVE: It is 1100 hours on D+5. 'B' Squadron 17/21
LANCERS has been carrying out reconnaissance in support of
8 brigade (part of 4 British Corps), when one of its recon-
naissance scout cars is hit by a rocket launcher. The
scout car is disabled and the driver is severely wounded
in the chest. Surgery is obviously required and a report
is sent to HQ 'B' Squadron, 17/21 LANCERS requesting cas-
ualty evacuation to 8 Advanced Dressing Station. The ac-
tion starts at Squadron HQ. (Calls would have preceded
this on Troop and Squadron Nets.) It is subsequently de-
cided that the casualty must be evacuated to a Field
Hospital for intensive surgical treatment. It is antic-
pated that with a 9-10 minute delay, casualties have only
a 90% chance of survival and that an 18-minute delay in
the overall evacuation plan is likely to result in deaths
and mission failure because the chance of survival has
fallen to 70%.

TACTICAL FUNCTION: REQUEST FOR HELICOPTER CASUALTY EVACUATION

Serial No.	FROM		TO		MESSAGE			Duration/Group	Time
	Unit	Location	Unit	Location	Text	Mode	Circuit		
1	Hq. 'B' Sqn. 17/21 LANCERS	PA 5500	RHZ 17/21 LANCERS	PV 4195	Requests helicopter to be sent to casualty location for evacuation	TP	Regimental Command Net Voice	2 Minutes 20 Groups	1108-1110 hrs D+5 (Immediate)
2	RHG 17/21 LANCERS	PV 4195	Heli 17/21 LANCERS	Airborne in area PV 5094	Orders Heli to divert and collect casualty at PV 581002 and lift to 8 Advanced Dressing Station (ADS) (Flying time 5 minutes) (Loading time 2 minutes)	TP	Regimental Command Net Voice	2 Minutes 20 Groups	1111-1113 hrs D+5 (Immediate)
3	Heli 17/21 LANCERS	Area PA 5800	RHQ 17/21 LANCERS	PV 4195	Reports airborne for 8 ADS and ETA (Flying time 10 minutes)	TP	Regimental Command Net Voice	2 Minutes 16 Groups	1120-1122 hrs D+5 (Priority)
4	Hq. 'B' Sqn. 17/21 LANCERS	PA 5500	Hq. 8 Bde.	PV 3390	Reports casualty evacuated and ETA	TP	Brigade Command Net Voice (for this operation 'B' Sqn. has a set on this net)	2 Minutes 16 Groups	1121-1123 hrs D+5 (Priority)
5	Hq. 8 Bde.	PV 3390	8 Advanced Dressing Station	PV 3287	Reports casualty evacuated and ETA	TP	Brigade Admin. Net	2 Minutes 16 Groups	1125-1127 hrs D+5 (Priority)
6	8 Advanced Dressing Station	PV 3287	Hq. 8 Bde.	PV 3390	Reports Evacuation of this and 10 other casualties to 3 Field Hospital	TP	Brigade Admin. Net	2 Minutes 16 Groups	1155-1157 hrs D+5 (Immediate)
7	Hq. 8 Bde.	PV 3390	Rear Hq. 4 Division	PV 0973	Requests evacuation of 11 casualties from 8 ADS to 3 Field Hospitals	TP	Telephone (or Teleprinter) Bruin Trunk System Alternative is Divisional Admin. Net	3 Minutes 23 Groups	1157-1200 hrs D+5 (Immediate)

TACTICAL FUNCTION MESSAGES

111

TACTICAL FUNCTION: REQUEST FOR HELICOPTER CASUALTY EVALUATION:

Serial No.	FROM Unit	FROM Location	TO Unit	TO Location	MESSAGE Text	Mode	Circuit	Duration/Group	Time
8	Rear Hq. 4 Division	PV 0973	4 Field Ambulance (Divisional Air Support Officer is located there)	PV 1176	Requests SH (Helicopter for evacuation of 11 casualties from 8 ADS to 3 Field Hospital)	TP	Telephone either on DBP Civil Circuit or by Locally Laid Wire Alternative is Div. Admin. Net to Div. Admin. Area or via the Medical Net	3 Minutes 23 Groups	1200-1203 hrs D+5 (Immediate)
9	Rear Hq. 4 Division	PV 0973	Rear Hq. 1 British Corps	NV 1066	Info. on CASEVAC	TP	Telephone Bruin Trunk System or via Corps Admin. Net	3 Minutes 23 Groups	1200-1203 hrs D+5 (Priority)
10	Rear Hq. 1 British Corps	NV 1066	3 Field Hospital	MV 8139	Info. on CASEVAC	TP	Telephone on DBP Civil Circuit	4 Minutes 23 Groups	1203-1207 hrs D+5 (Priority)
11	(4 Field Ambulance) Divisional Air Support Officer	PV 1176	Heli Sqn. (RAF) (Info. FATOC)	PV 0561	Request Heli for CASEVAC and gives details	TP	HF SSB Net Radio	3 Minutes 23 Groups	1205-1208 hrs D+5 (Immediate)
12	Heli Sqn. (RAF)	PV 0561	No. 1 Heli Sub-site (RAF)	PV 1082	Gives orders on Heli for CASEVAC	TP	VHF Net Radio	2 Minutes 20 Groups	1208-1210 hrs D+5 (Priority)
13	No. 1 Heli Sub-site (RAF)	PV 1082	Divisional Air Support Officer (at 4 Field Ambulance)	PV 1176	Reports ETA of Heli at 8 Advanced Dressing Station	TP	HF SSB Net Radio	2 Minutes 15 Groups	1212-1214 hrs D+5 (Priority)
14	4 Field Ambulance (Divisional Air Support Officer)	PV 1176	Rear Hq. 4 Division	PV 0973	Reports ETA of Heli at 8 Advanced Dressing Station	TP	Telephone either on DBP Civil Circuit or by Locally Laid Wire. Alternative is Div.	2 Minutes 15 Groups	1214-1216 hrs D+5 (Priority)

TACTICAL FUNCTION MESSAGES

112

TACTICAL FUNCTION: REQUEST FOR HELICOPTER CASUALTY EVACUATION

Serial No	FROM		TO		MESSAGE				
	Unit	Location	Unit	Location	Text	Mode	Circuit	Duration/Group	Time
14	Continued						Admin. Area or via the Med. Medical Net		
15	Rear Hq. 4 Division	PV 0973	Hq. 8 Bde.	PV 3390	Reports ETA of Heli at 8 Advanced Dressing Station	TP	Telephone or Teleprinter via Bruin Trunk System Alternative is Admin. Net	2 Minutes 15 Groups	1216-1218 hrs D-5 (Priority)
16	Hq. 8 Bde.	PV 3390	8 Advanced Dressing Station	PV 3287	Reports ETA of Heli at 8 Advanced Dressing Station	TP	Brigade Admin. Net	2 Minutes 15 Groups	1218-1220 hrs D-5 (Priority)
	(20 Minutes flying time to 8 ADS -- 8 Minutes loading 11 CAS.)								
17	SH Heli (RAF)	Airborne in Area PV 3287	Rear Hq. 1 British Corps (FATOC) (Heli Sqn. and No. 1 Heli Sub-site Copy)	NV 1066	Airborne and ETA at 3 Field Hospital 60 minutes - 5 minutes unloading 11 CAS)	TP	HFSSB	2 Minutes 15 Groups	1240-1242 hrs D-5 (Priority)
18	Rear Hq. 1 British Corps	NV 1066	3 Field Hospital	MV 8139	ETA of CASEVAC Heli at 3 Field Hospital	TP	Telephone on DBP Civil Circuit	2 Minutes 15 Groups	1242-1244 hrs D-5 (Priority)
19	Rear Hq. 1 British Corps	NV 1066	SH Heli	Airborne for MV 8139	Tasks Heli with load from 1 Corps Ordnance Maintenance. Park to 8 Ordance Fd Park (on completion of present mission) casualties unloaded	TP	HFSSB	3 Minutes 27 Groups	1322-1325 hrs D-5 (Routine)
									1345 hrs D-5

TACTICAL FUNCTION MESSAGES

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TACTICAL FUNCTION: REQUEST FOR HELICOPTER CASUALTY EVACUATION UK D+5 PHASE II

	RHQ 17/21L	8 Advanced Dressing Statir t	HQ 8 BDE.	Rear HQ 4 Division	4 Field Ambulance (Division Air Support Officer)	Rear Hq. 1 British Corps	Heli-Squadron RAF	Number 1 Heli-Sub-site RAF	Heli-RAF
B Squadron 17/21L	▨								
Heli-17/21L	▨								
HQ. 8 Bde.		▨	▨						
Rear Hq. 4 Division				▨					
4 Fd Ambulance (Div. Air Sup'l. Officer)					X*	▨			
Rear Hq. 1 BR Corps (FATOC)					▨	▨	▨		
3 Fd. Hospital						▨		▨	
Heli-RAF								▨	

Need Line Matrix

*Using Div. Admin. Nel at 4 Field Amb.

APPENDIX C

TACTICAL FUNCTION: CLOSE AIR SUPPORT OF FORWARD TROOPS –
DIRECT TASKING BY BRIGADE

NUMBER: 22

NARRATIVE: It is 1500 hours. B Coy Royal Anglians (under
command 19 Infantry Brigade) reports heavy mortar and
small arms fire from enemy troops who are dug in around
farm buildings on the NE corner of the airstrip at XB 0617.
B Coy is tied down in defensive positions and is being
denied the use of the airstrip which must be cleared by
1630 hours to allow two resupply aircraft scheduled to land,
unload and take off in daylight, (airstrip facilities are
limited to handling one resupply aircraft at a time). The
Air Commander has placed the 8 Harrier Fighter ground-attack
aircraft based at XB 5053 under operational control of 19
Brigade during this period: 19 Brigade (Brigade Air Support
Operations Center) tasks 4 Harriers from XB 5053 to carry
out a ground attack mission on the reported enemy positions.

TACTICAL FUNCTION: CLOSE AIR SUPPORT OF FORWARD TROOPS - DIRECT TASKING BY BRIGADE

Serial No.	FROM Unit	FROM Location	TO Unit	TO Location	MESSAGE Text	Mode	Circuit	Duration/Group	Time
1	B Coy R. Anglian	XB 0617	Bn Hq 2 R. Anglian	XB 1515	Call for air support	TP	Bn Net Radio	1 Minute	1502-1503 hrs (Immediate)
2	Bn Hq 2 R. Anglian	XB 1515	19 Bde Hq (G Staff)	XB 4953	Relays call for air support with amplifying detail	TP	Bde Command Net Radio	2 Minutes	1504-1506 hrs (Immediate)
3	19 Bde Hq. (G Staff)	XB 4953	Bn Hq 2 R. Anglian	XB 1515	Task Accepted	TP	Bde Command Net	1/2-Minute	1507 hrs (Priority)
4	19 Bde Hq. (BASOC)	XB 4953	19 Bde Airhead (TAC OPS)	XB 5053	Air tasking message encoded for transmission on insecure circuit	TP	Offensive Air Support Net Radio	2 Minutes	1522-1524 hrs (Immediate)
5	19 Bde Airhead (TAC OPS)	XB 5053	19 Bde Hq. (BASOC)	XB 4953	Accepts task	TP	Offensive Air Support Net Radio	1/2-Minute	1525 hrs (Immediate)
6	19 Bde Hq. (BASOC)	XB 4953	Joint Force Hq (ASOC)	YB 9208	Copies air tasking message for info.	TT	ALN/TAR Net Radio	40 Groups	1525-1527 hrs (Routine)
7	19 Bde Airhead (TAC OPS)	XB 5053	19 Bde Hq. (BASOC)	XB 4953	Time On Target (TOT) message	TP	Offensive Air Support Net Radio	1 Minute	1529-1530 hrs (Immediate)
8	19 Bde Hq. (G Staff)	XB 4953	Bn Hq 2 R. Anglian	XB 1515	TOT Message; FAC ordered Airborne for control of attack	TP	Bde Command Net / Brigade Artillery Net	1 Minute	1530-1531 hrs (Immediate) 1530-1537 hrs (Immediate)
9	Battalion Hq. 2 R. Anglian	XB 1515	B Coy 2 R. Anglian	XB 0617	TOT Message	TP	Battalion Net Radio	1 Minute	1531-1532 hrs (Immediate)
10	19 Brigade Hq. (G Staff)	XB 4953	Battalion Hq. 2 P. Anglian	XB 1515	In flight strike report	TP	Brigade Command Net	1/2-Minute	1542 hrs (Immediate)
11	19 Brigade Airhead (TAC OPS)	XB 5053	19 Brigade Hq. (BASOC)	XB 4953	MISREP - encoded for transmission on insecure circuit	TP	Offensive Air Support Net Radio	3 Minutes	1610-1613 hrs (Priority)

TACTICAL FUNCTION MESSAGES

TACTICAL FUNCTION: CLOSE AIR SUPPORT OF FORWARD TROOPS - DIRECT TASKING BY BRIGADE

Serial No.	FROM Unit	FROM Location	TO Unit	TO Location	MESSAGE Information	Mode	Circuit	Duration/Group	Time
12	19 Brigade Hq.	XB 4953	Battalion Hq. 2 R. Anglian	XB 1515	MISREP	TP	Brigade Command Net	3 Minutes	1613-1616 hrs (Priority)
			Joint Force Hq. (ASOC)	YB 9208	MISREP copy for Information	TT	ALN/TAR Net Radio	50 Groups	1613-1616 hrs (Priority)
13	19 Brigade Airhead (TAC OPS)	XB 5053	19 Brigade Hq. (BASOC)	XB 4953	HOT PHOTO REP encoded for transmission on insecure circuit	TP	Offensive Air Support Net Radio	2 Minutes	1645-1647 hrs (Priority)
14	19 Brigade Hq.	XB 4953	Battalion Hq. 2 R. Anglian	XB 1515	HOT PHOTO REP.	TP	Brigade Command Net	2 Minutes	1647-1649 hrs (Priority)
			Joint Force Hq. (ASOC)	YB 9208	HOT PHOTO REP. copy for information	TT	ALN/TAR Net Radio	25 Groups	1647-1649 (Priority)

TACTICAL FUNCTION MESSAGES

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APPENDIX D

SAMPLE PROBLEM CALCULATIONS

LINK LOADING TABLES

1ST ITERATION

TRAFFIC	BQ-DA	BQ-DM	DA-DM	DA-DMSF	DM-AA	DM-AASF
BQ-DA	46.0	3.6	0.6	3.5	0	0
BQ-DM	8.8	107.0	1.4	8.3	0	0
BQ-AA	2.5	27.6	0	2.5	0	33.4
CA-DM	0	0	42.0	39.0	0	0
DA-AA	0	0	10.0	21.9	11.0	24.3
DM-AA	0	0	0	0	58.0	47.0
TOTAL	57.3	138.2	54.0	75.2	69.0	104.7
C	3	3	4	2	2	2
A	0.95	2.3	0.90	1.08	1.15	1.74
C/A	1.46	4.28	1.29	2.17	1.40	7.69

2ND ITERATION

TRAFFIC	BQ-DA	BQ-DM	DA-DM	DASF-DMSF	DM-AA	DMSF-AASF
BQ-DA	46.0	0.99	0.21	1.25	0	0
BQ-DM	44.2	107.0	21.3	37.3	0	26.4
BQ-AA	2.0	3.0	0	2.0	0	0
DA-DM	0	0	42.0	39.0	0	0
DA-AA	0	0	11.5	3.2	11.8	16.8
DM-AA	0	0	0	0	58.0	47.0
TOTAL	92.2	111.0	75.0	82.8	69.8	90.2
C	3	3	4	2	4	2
A	1.54	1.85	1.25	1.38	1.16	1.50
C/A	2.05	2.61	1.45	3.23	1.41	4.0

3RD ITERATION

TRAFFIC	BQ-DA	BQ-DM	DA-DM	DASF-DMSF	DM-AA	DMSF-AASF
BQ-DA	46.0	3.65	1.02	-6.12	0	0
BQ-DM	19.1	107.0	11.24	19.13	0	0
BQ-AA	1.5	7.5	0	1.5	0	25.3
DA-DM	0	0	42.0	39.0	0	0
DA-AA	0	0	11.1	4.2	11.5	11.8
DM-AA	0	0	0	0	58.0	47.0
TOTAL	66.6	118.2	65.4	70.0	69.5	84.1
C	3	3	4	2	4	2
A	1.11	1.97	1.09	1.17	1.16	1.40
C/A	1.59	2.91	1.37	2.41	1.41	3.33

4TH ITERATION

TRAFFIC	BQ-DA	BQ-DM	DA-DM	DASF-DMSF	DM-AA	DMSF-AASF
BQ-DA	46.0	1.58	0.45	2.63	0	0
BQ-DM	29.5	107.0	15.8	25.0	0	0
BQ-AA	2.2	8.8	0	2.2	0	25.9
DA-DM	0	0	42.0	39.0	0	0
DA-AA	0	0	11.3	4.7	11.6	14.3
DM-AA	0	0	0	0	58.0	47.0
TOTAL	77.7	117.4	69.6	73.6	69.6	87.2
C	3	3	4	2	4	2
A	1.30	1.96	1.16	1.23	1.16	1.45
C/A	1.76	2.88	1.41	2.60	1.41	2.64

5TH ITERATION

TRAFFIC	BQ-DA	BQ-DM	DA-DM	DASF-DMSF	DM-AA	DMSF-DASF
BQ-DA	46.0	2.7	0.65	3.9	0	0
BQ-DM	26.2	107.0	14.2	23.5	0	25.90
BQ-AA	2.46	7.59	0	2.46	0	0
DA-DM	0	0	42.0	39.0	0	0
DA-AA	0	0	11.2	5.55	11.6	14.3
DM-AA	0	0	0	0	58.0	47.0
TOTAL	74.7	117.3	68.1	74.4	69.6	87.2
C	3	3	4	2	4	2
A	1.25	1.96	1.14	1.24	1.16	1.44

1st Iteration

K	L	M	N
0	1	1	1
1	0.95	0.95	1.95
	2.30	2.30	3.30
	0.91	0.93	1.90
	1.08	1.08	2.08
	1.15	1.15	2.15
	1.74	1.74	2.74
2	0.47	0.45	2.43
	1.15	2.64	5.94
	0.45	0.40	2.30
	[0.54	0.58]	
	0.55	0.65	2.80
	[0.82	1.51]	
3	[0.32	0.14]	
	[0.77	2.03]	
	0.30	0.12	2.42
	0.38	0.25	3.05
4	0.23	0.028	
	0.29	0.073	

3rd Iteration

Y	L	M	N
0	1	1	1
1	1.11	1.11	2.11
	1.97	1.97	2.97
	1.09	1.09	2.09
	1.17	1.17	2.17
	1.16	1.16	2.16
	1.40	1.40	2.40
2	0.56	0.62	2.73
	0.99	1.95	4.92
	0.55	0.60	2.69
	[0.59	0.69]	
	0.58	0.67	2.83
	[0.70	0.98]	
3	[0.37	0.23]	
	[0.66	1.37]	
	0.36	0.22	2.91
	0.39	0.26	3.09
4	0.28	0.062	
	0.29	0.075	

2nd Iteration

K	L	M	N
0	1	1	1
1	1.54	1.54	2.54
	1.85	1.85	2.85
	1.25	1.25	2.25
	1.38	1.38	2.38
	1.16	1.16	2.16
	1.50	1.50	2.50
2	0.77	1.19	3.73
	0.93	1.72	4.57
	0.63	0.79	3.04
	[0.69	0.95]	
	0.58	0.67	2.83
	[0.75	1.13]	
3	[0.51	0.61]	
	[0.62	1.07]	
	0.42	0.33	3.37
	0.39	0.26	3.09
4	0.31	0.10	
	0.29	0.07	

4th Iteration

K	L	M	N
0	1	1	1
1		1.30	2.30
		1.96	2.96
		1.16	2.16
		1.45	2.45
2	0.65	0.85	3.15
	0.98	1.92	4.88
	0.58	0.67	2.83
	[0.62	0.76]	
	0.58	0.67	2.83
	[0.73	1.06]	
3	[0.43	0.37]	
	[0.65	1.25]	
	0.39	0.26	3.09
	0.39	0.26	3.09
4	0.29	0.075	
	0.29	0.075	

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1ST ITERATION	3RD ITERATION
$\dfrac{1.46}{\underset{0.14}{1.46 + 2.40}} = 0.078$	$\dfrac{1.59}{\underset{.23}{1.59 + 2.73}} = 0.118$
$\dfrac{4.28}{\underset{2.03}{4.28 + 5.94}} = 0.594$	$\dfrac{2.91}{\underset{1.29}{2.91 + 4.92}} = 0.433$
$\dfrac{1.29}{\underset{.028}{1.29 + 2.42}} = 0.014$	$\dfrac{1.37}{\underset{.062}{1.37 + 2.91}} = 0.028$
$\dfrac{2.17}{\underset{0.58}{2.17 + 2.08}} = 0.377$	$\dfrac{2.41}{\underset{.69}{2.41 + 2.17}} = 0.434$
$\dfrac{1.40}{\underset{.073}{1.40 + 3.05}} = 0.032$	$\dfrac{1.41}{\underset{.075}{1.41 + 3.09}} = 0.033$
$\dfrac{7.69}{\underset{1.51}{7.69 + 2.74}} = 0.809$	$\dfrac{3.33}{\underset{.98}{3.33 + 2.40}} = 0.576$

2ND ITERATION	4TH ITERATION
$\dfrac{2.05}{\underset{.61}{2.05 + 3.73}} = 0.251$	$\dfrac{1.76}{\underset{.37}{1.76 + 3.15}} = 0.171$
$\dfrac{2.61}{\underset{1.07}{2.61 + 4.57}} = 0.379$	$\dfrac{2.88}{\underset{1.25}{2.88 + 4.88}} = 0.425$
$\dfrac{1.45}{\underset{.10}{1.45 + 3.37}} = 0.041$	$\dfrac{1.41}{\underset{.075}{1.41 + 3.09}} = 0.033$
$\dfrac{3.23}{\underset{.95}{3.23 + 2.38}} = 0.564$	$\dfrac{2.60}{\underset{.76}{2.60 + 2.23}} = 0.470$
$\dfrac{1.41}{\underset{.07}{1.41 + 3.09}} = 0.031$	$\dfrac{1.41}{\underset{.075}{1.41 + 3.09}} = 0.033$
$\dfrac{4.0}{\underset{1.13}{4.0 + 2.50}} = 0.644$	$\dfrac{3.64}{\underset{1.06}{3.64 + 2.45}} = 0.612$

CALCULATIONS OF ALGORITHM TABLE 2

TABLE OF YB

B =	67	33	2
Y = 2	1 33	67	.4
Y = 3	2.0	1 0	6
Y = 4	2 67	1 33	8
Y = 5	3 33	1 67	1 0
Y = 6	4 0	2 0	1 2

LEGEND OF UNIT BOX

	B VALUES			TABLE
C = 2	67	000	000	
	33	000	000	
	2	000	000	
C = 3	67	000		000
	33	000		000
	2	000		000
C = 4	2	000		
		A = 1	A = 1 5	A = 2

S₁ block

3 67	375	563	S_1
2 33	429	644	
2 2	455	683	
3 67	272		54
3 33	3		6
3 2	313		63
R_1			
4.2	238		

Row 2

S_2:

3 33	.3	45	S_2
2 67	375	563	
2 4	417	626	
4 33	23		46
3 67	272		54
3 4	294		59
R_2			
4 4	227		

T_2:

113	253	T_2
161	363	
19	428	
063	.25	
082	32	
092	37	
054		

$2T_2$:

226	506	$2T_2$
372	726	
38	856	
126	50	
164	64	
184	74	
.108		

U_2:

.488	816	U_2
.590	1 007	
645	1 111	
335	79	
382	92	
405	1 00	
.292		

V_2:

.6	1 07	V_2
75	1.37	
83	1.64	
4	1 04	
46	1 24	
.50	1.37	
34		

Row 3

S_3:

4.0	25	375	S_3
3 0	33	5	
2 6	38	57	
5.0	.2		.4
4 0	25		5
3.6	28		.56
R_3			
4.6	22		

T_3:

028	095	T_3
.053	182	
.072	.244	
013	.1	
.021	16	
.026	.21	
.012		

$3T_3$:

084	.285	$3T_3$
.159	546	
.216	732	
039	.3	
.063	48	
.078	.63	
.036		

U_3:

.516	.911	U_3
.643	1.189	
.717	1.355	
348	890	
403	1 080	
431	1.210	
.304		

V_3:

.684	1.355	V_3
909	1 916	
1 046	2 272	
439	1 340	
523	1 720	
578	2 000	
.376		

Row 4

S_4:

4.67	21	32	S_4
3 33	3	45	
2.8	36	54	
5 67	18		.36
4.33	23		46
3.8	26		.52
R_4			
4 8	21		

T_4:

.006	.030	T_4
.016	.082	
.026	.132	
.002	.036	
.005	.074	
.007	.109	
.003		

$4T_4$:

.024	.120	$4T_4$
.064	.323	
.104	.528	
.008	.144	
.020	.296	
.028	.436	
.012		

U_4:

.522	.941	U_4
.659	1.271	
.743	1.487	
350	.926	
408	1.154	
438	1.319	
.307		

V_4:

708	1.475	V_4
973	2.244	
1.150	2.800	
447	1 484	
543	2.016	
606	2.436	
.388		

Row 5

S_5:

5.33	.18	.27	S_5
3.67	.27	.41	
3 0	33	5	
6.33	16		.32
4.67	21		.42
4 0	25		.5
R_5			
5.0	.2		

T_5:

.001	.008	T_5
.004	.034	
009	.066	
0003	.012	
001	.031	
.002	.056	
.0006		

$5T_5$:

.005	.040	$5T_5$
.020	.170	
.045	.330	
.0015	.060	
.005	.155	
.010	.280	
.0030		

U_5:

.523	.949	U_5
.663	1.305	
.752	1.553	
350	.938	
409	1.185	
440	1.375	
.308		

V_5:

.713	1.515	V_5
993	2.414	
1.195	3.130	
449	1.544	
548	2.171	
616	2.716	
.391		

Row 6

S_6:

6 0	166	249	S_6
4 0	25	375	
3.2	313	.470	
7 0	.143		.286
5 0	2		.4
4.2	238		.476
R_6			
5.2	192		

T_6:

.00017	.002	T_6
.00100	.013	
.00282	.031	
.000043	.0034	
0002	.0123	
.00048	.0267	
.00001		

$6T_6$:

.001	.012	$6T_6$
.006	.078	
.017	.186	
0	.020	
.001	.074	
.003	.160	
0		

U_6:

.523	.951	U_6
.664	1.318	
.755	1.584	
350	.941	
409	1.197	
440	1.402	
.308		

V_6:

714	1.527	V_6
1.000	2.492	
1.212	3.310	
449	1.564	
549	2 245	
619	2.876	
.391		

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CALCULATIONS OF ALGORITHM TABLE 1

0.67 0.33 0.2	0.45 0.22 0.13	b/a
0.67 0.33 0.2		0.33 0.17 0.1
0.2		

K	L	M	N
0	1	1	1
1	1 1.5 2	1 1.5 2	2 2.5 3
2	0.5 0.75 1.0	0.5 1.13 2.0	2.5 3.63 5.0
3	0.33 0.5 0.67	0.17 0.57 1.33	2.67 4.20 6.33
4	0.25 0.38 0.50	0.043 0.217 0.67	2.713 4.417 7.0

2.5 2.5 2.5	3.63 3.63 3.63	N
2.67 2.67 2.67		6.33 6.33 6.33
2.71		

0.5 0.5 0.5	1.13 1.13 1.13	M
0.17 0.17 0.17		1.33 1.33 1.33
0.043		

PROBABILITY OF DELAY

$$\underline{a = 1 \quad c = 2}$$
$$P(\delta > 3) = \frac{(.67)(.714)}{\frac{2.5}{.5} + .523} = .087$$

$$P(\delta > 6) = \frac{(.33)(1.0)}{5 + .664} = .058$$

$$P(\delta > 10) = \frac{(.2)(1.21)}{5 + .755} = .042$$

$$\underline{a = 1.5 \quad c = 2}$$
$$P(\delta > 3) = \frac{(.45)(1.527)}{\frac{3.63}{1.13} + .951} = .165$$

$$P(\delta > 6) = \frac{(.22)(2.492)}{3.212 + 1.318} = .121$$

$$P(\delta > 10) = \frac{(.13)(3.31)}{3.212 + 1.584} = .090$$

$$\underline{a = 1 \quad c = 3}$$
$$P(\delta > 3) = \frac{(.67)(.449)}{\frac{2.67}{.17} + .350} = .019$$

$$P(\delta > 6) = \frac{(.33)(.549)}{15.7 + .409} = .011$$

$$P(\delta > 10) = \frac{(.2)(.619)}{15.7 + .440} = .008$$

$$\underline{a = 1 \quad c = 4}$$

$$P(\delta > 10) = \frac{(1.2)(.391)}{\frac{2.71}{.043} + .308} = .001$$

$$\underline{a = 2 \quad c = 3}$$
$$P(\delta > 3) = \frac{(.33)(1.564)}{\frac{6.33}{1.33} + .941} = .091$$

$$P(\delta > 6) = \frac{(.17)(2.245)}{4.76 + 1.197} = .064$$

$$P(\delta > 10) = \frac{(.1)(2.876)}{4.76 + 1.402} = .047$$

RESULTS ARE PLOTTED ON GRAPH IN FIGURE D-1.

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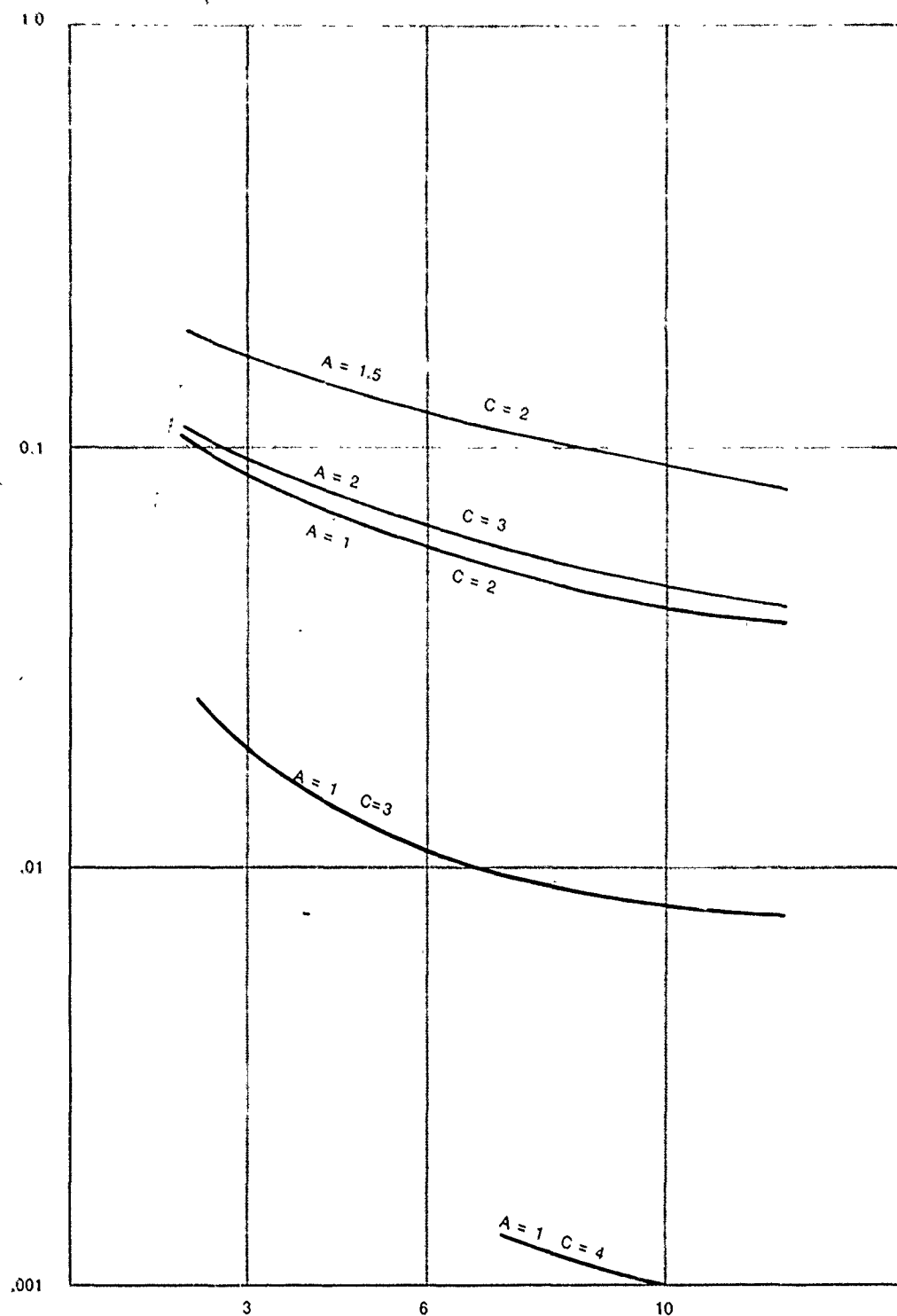
Figure D-1. Probability of Delay Results

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DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
Communications & Systems, Incorporated Wash., D.C.; Paramus, N.J.; Boston, Mass.	Unclassified
	2b. GROUP

3. REPORT TITLE

Development of Criteria and Measures of Effectiveness for U.S. Army Tactical Communication Systems

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final

5. AUTHOR(S) (First name, middle initial, last name)

George D. Weinstock   Marvin Douglas   Benjamin Blom

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
May 1969	133	15

8a. CONTRACT OR GRANT NO	9a. ORIGINATOR'S REPORT NUMBER(S)
DAAB07-69-D-5012	
b. PROJECT NO.	
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

10. DISTRIBUTION STATEMENT

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Systems/Cost Analysis Office U.S. Army Electronics Command Ft. Monmouth, New Jersey

13. ABSTRACT

The purpose of this study is to develop a workable and valid method for measuring the effectiveness of the broad spectrum of U.S. Army tactical communication systems and equipments. To this end, an evaluation concept was formulated which provided an integrated system effectiveness model capable of providing a single explicit measure of system effectiveness for proposed tactical communication systems. The effort performed was divided into four parts: (1) the development of a comprehensive list of performance factors and effectiveness criteria which serve as input data to the model; (2) the development of matrices to relate military operations in the tactical environment and communication requirements; (3) to formulate analytic relationships between performance factors, criteria, and measures of effectiveness; and (4) to develop the system effectiveness model. The operation of the model is demonstrated by means of a sample problem.

DD FORM 1 NOV 65 **1473**

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Tactical Communication Systems						